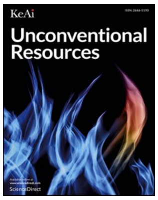
Unconventional Resources 5 (2025) 100121

Contents lists available at ScienceDirect

Unconventional Resources

journal homepage: www.keaipublishing.com/en/journals/unconventional-resources/



Insight into organic photovoltaic cell: Prospect and challenges

Charity M. Nkinyam [b], Chika Oliver Ujah [a,b,*], Kingsley C. Nnakwo [c,**], Daramy V.V. Kallon [a]

[a] *Department of Mechanical and Industrial Engineering Technology, University of Johannesburg, P.O. Box 524, Johannesburg, 2006, South Africa*
[b] *Africa Centre of Excellence for Sustainable Power and Energy Development (ACE-SPED), University of Nigeria, Nsukka, 410001, Nigeria*
[c] *Department of Metallurgical and Materials Engineering, Nnamdi Azikiwe University, Awka, Nigeria*

ARTICLE INFO

Keywords:
Renewable energy
Organic photovoltaics
Third generation
Power conversion efficiency
Photovoltaic cells
Photovoltaic technology: degradation
Challenges

ABSTRACT

Organic photovoltaics have attracted considerable interest in recent years as viable alternatives to conventional silicon-based solar cells. The present study addressed the increasing demand for alternative energy sources amid greenhouse gas emissions and rising traditional energy costs. OPV cells hold multiple benefits compared to their inorganic equivalents, including high flexibility, low weight, and the promise of inexpensive solution manufacturing. Typically, the active layer OPV cells comprise a blend of electron-donating and electron-receiving organic materials that may absorb a wide range of sunlight on adjustment. Recent breakthroughs in materials science and device engineering have led to significant advancements in OPV, including non-fullerene acceptors and efficiency exceeding 19.6 %, highlighting a transformative shift towards more efficient and eco-friendly energy alternatives. The review addressed the prospects and challenges of this innovative technology, outlining current limitations and proposing efficiency improvement strategies involving photo-protective mechanisms, stable material design, and approaches to comprehend and enhance OPV performance. Despite the promising outlook, challenges such as degradation and stability issues, power conversion efficiency, and manufacturing complexities remain substantial barriers that need resolution for widespread adoption. In conclusion, the study advocated for future research in OPV technology to focus on innovative approaches, technological advancements, and collaborative efforts toward novel materials development, creative engineering solutions, and optimized device architectures, enhancing the effectiveness and stability of OPV cells. This review emphasized the urgency of tackling such problems to fully exploit the opportunities offered by OPVs for a greener and more efficient energy future.

1. Introduction

In developing countries, electricity is pivotal in driving rapid economic growth, creating immense pressure on energy infrastructure to meet the escalating demand as populations expand [1,2]. More than a billion people in Third World small villages face challenges in connecting to the grid due to impractical grid extensions caused by dispersed populations, bad topographies, and the high costs associated with extending the grid, rendering it economically unfeasible for profit-oriented power utilities [3,4]. The insufficient power supply in the region is estimated to result in a 3.15 % annual business loss and contributing to 1.55 million deaths, particularly among children and women, due to biomass smoke [5]. Inadequate clean and sustainable energy in rural areas, poses significant challenges to economic and technological development at all levels [6,7]. Renewable energy is an essential alternative to conventional fuels to minimize the negative impacts of climate change [8,9]. Hazard-free renewable energy sources (water, earth's crust, biological materials, sun, and wind) contribute to the concept of sustainable energy, ensuring the fulfillment of society's current and future requirements while safeguarding the environment [10,11]. Solar energy evolves through photovoltaic systems, which capture sunlight and convert it into electrical or thermal energy for residential or industrial applications [12]. Solar PV has recently been recognized as the most beneficial source of electricity and is currently the world's most economical form of electricity generation [13]. The overall capacity of the worldwide photovoltaic (PV) market has increased dramatically over the past two decades from a mere 252 MW in 2000 to 1589 GW at the end of 2023 [14–16], representing a stable growth of 40 % per year for 20 years and the overall worldwide capacity

---

* Corresponding author. Department of Mechanical and Industrial Engineering Technology, University of Johannesburg, P.O. Box 524, Johannesburg, 2006, South Africa.
** Corresponding author.
E-mail addresses: chikau@uj.ac.za (C.O. Ujah), kc.nnakwo@unizik.edu.ng (K.C. Nnakwo).

https://doi.org/10.1016/j.uncres.2024.100121
Received 29 April 2024; Received in revised form 30 August 2024; Accepted 24 September 2024
Available online 24 September 2024
2666-5190/© 2024 The Authors. Publishing services by Elsevier B.V. on behalf of KeAi Communications Co. Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

Abbreviations

a-Si	amorphous silicon
BIPV	building integration photovoltaic
BHJ	bulk heterojunction
c-Si	crystalline silicon
CIGS	copper-indium-gallium-selenide
CdTe	cadmium telluride
ETL	electron transport layer
FA	fullerene acceptors
FF	fill factor
GaAs	gallium arsenide
HOMO	highest occupied molecular orbital
HTL	hole transport layer
I_{sc}	short circuit current
LUMO	least unoccupied molecular orbital
NFA	non-fullerene acceptors
OPV	organic photovoltaic cell
OSC	organic solar cells
PCE	power conversion efficiency
PCBM	phenyl-C61-butyric acid methyl ester
PEN	polyethylene naphthalate
PEDOT	poly (3,4-ethylenedioxythiophene)
PSS	poly (styrene sulfonate)
PET	polyethylene terephthalate
P_{max}	Maximum power
PV	photovoltaics
P3HT	poly (3-hexylthiophene)
R2R	Roll-to-roll
UV	Ultra-violet radiation
Voc	Open circuit voltage

installed is projected to reach a total of 2840 GW by the year 2030 [17]. Photovoltaic market shares spread across a range of thin-film technology types.

For many years, the market for silicon-based PV technologies has been driven by silicon's excellent charge transport properties and its abundance in the Earth's crust, achieving efficiency rates of around 25 % [18]. However, organic photovoltaic (OPV) cell technology has emerged as a potentially cheaper form of electricity, surpassing silicon-based photovoltaic technology [19].

The development of more efficient photovoltaic cells relies heavily on molecular architecture and electron acceptor properties. Fullerenes have extended active layer composition and performance metrics but exhibit symmetric chemical structures, poor synthetic flexibility, and limited light-harvesting properties. High manufacturing costs limit their commercialization [20]. The search for alternative electron acceptor materials is motivated by high light and oxygen sensitivity and degradation mechanisms [21].

Non-fullerene acceptors have revolutionized organic photovoltaics by offering customizable molecular structures, enabling precise energy levels and absorption characteristics, making them ideal for customizing materials for specific applications [20,22]. Non-fullerene materials offer excellent stability and resistance to degradation, making them more durable and long-lasting, crucial for organic photovoltaic device performance [23], compared to FA, which suffers from instability and a tendency to undergo macroscopic degradation under thermal stress [21, 23]. The use of NFA in OSC has significantly improved efficiency, photochemical stability, and mechanical durability, paving the way for a new era of renewable energy [24]. The efficiency of NFA-based OPVCs has significantly outperformed those based on FAs due to rapid molecular design advancements exceeding 19.2 %, up from 11 % in 2010 [25–27].

Nevertheless, with its captivating prospects and quick development, OPV hasn't yet been a widely adopted commercial technology as it has PCE, far below that of its corresponding non-organic partners. Many research studies have revealed organics, inorganic, and composites that may eventually substitute the silicon materials used in the current solar cell technology [28]. The inherent qualities of organic materials (polymers and tiny molecules) guarantee their recent applications in PV solar cells. Organic electronics, a subfield, employs these materials to transmit and absorb light, with OPV technology being a direct light-to-energy conversion technology [29]. Despite the benefits of low cost of production, lightweight, and semi-transparent properties, challenges remain for OPVs, including improving stability, increasing efficiency, and addressing environmental degradation under ambient conditions [30–32]. Photo-protective mechanisms (UV absorbers and stabilizers) help prevent the degradation of active materials and device components after exposure to light, oxygen, and moisture. These strategies extend operational life and maintain high performance by preventing harmful UV radiation from reaching sensitive donor and acceptor components susceptible to photochemical reactions [33].

Photovoltaic (PV) cell technology attracts considerable attention based on its significant ability to offer cleaner, environmentally friendly, and sustainably produced energy. This review provides a holistic view of organic photovoltaic cells, emphasizing the prospects and challenges.

1.1. *Review objectives*

The review adds a great deal to the body of knowledge already available on OPV cells, some of which include:

- To explore the evolution and classification of photovoltaic (PV) cell technology and examine three distinct generations to understand their emergence and development processes.
- To explore the operating mechanisms and device architectures of OPV cells. Compare their structures and evaluate their advantages and disadvantages.
- To review the electrical properties, performance, and efficiency of photovoltaic (OPV) cells, highlighting current developments, trends, and challenges.

1.2. *Review purpose*

This study aims to produce more sustainable and effective organic photovoltaic cells for a greener future by addressing the challenges and limitations. These challenges include their lower efficiency, improved stability, durability, and the requirement for scalable production methods that use hazard-free solvents and adequate processing temperature.

1.3. *Review scope*

In this review, we carried out a holistic assessment of the prospects, challenges, and emerging trends in OPVs. Recognizing the challenges and limitations inherent in organic photovoltaics, the pressing need for an increase in conversion efficiency and an optimization of stability is crucial for the advancements and commercialization of this technology. Moreover, the ecological impact of OPV highlights its potential as a low-carbon energy generation technology, making a valuable contribution to global sustainability efforts.

2. Literature review

2.1. Evolution of PV cell technology

The PV cell technology originates after the report by Alexandre Edmond Becquerel during his first observations of the photovoltaic effect in 1839 [34]. Russell Ohi marked a significant advancement in 1946 by creating the first contemporary silicon photovoltaic cell [34]. The utilization of organic technology, conceived by Chapin, is currently poised to revolutionize the global photovoltaic (PV) industry. Modern PV technology relies on thin silicon wafers for energy conversion (sunlight energy into electrical energy) [35]. This advanced technology operates on the principle of electron-hole pairing, as illustrated in Fig. 1 [35]. The fundamental philosophy of improved PV cells is light trapping, wherein the surface of the cell absorbs incoming light in a semiconductor, improving absorption over several passes due to the layered surface structure of silica-based PV cells, reflecting sunlight from the silicon layer to the cell surfaces [36]. Each cell contains a p-n junction comprising two different semiconductor layers. When high-energy photons hit the p-n junction, electrons are released. These electrons absorb the light energy and move to a different layer, leaving behind a hole and generating electricity [37].

2.2. PV cell technologies

Fig. 2 shows the classifying PV cell technologies. It involves three generations, representing distinct advancements in solar cell technology. The first, second, and third generations encompass various solar cell types [38]. While the technology of first and second-generation solar cells is notable, they exhibit the limitation of relying on silicon as an energy-intensive substance that is rare, expensive, and challenging to source in the required purity [39]. In contrast, third-generation PV technology introduces new components primarily based on silicon, enabling the production of economical and efficient devices [40]. This generation includes diverse solar cell types such as dye-sensitized, perovskite, OPV, quantum dots, and multilayer cells [41,42].

2.2.1. First generation photovoltaic cell technology: silicon cell

The photovoltaic cell of the first generation technology, particularly crystalline silicon, stands out as a widely adopted and popular choice for residential use. Its high power efficiency and extended lifetime promote its prominence in the residential solar energy sector.

Crystalline silicon is a dominant and extensively used material in photovoltaic cell technologies. This technology relies on crystalline silicon as the semiconducting component for manufacturing solar cells.

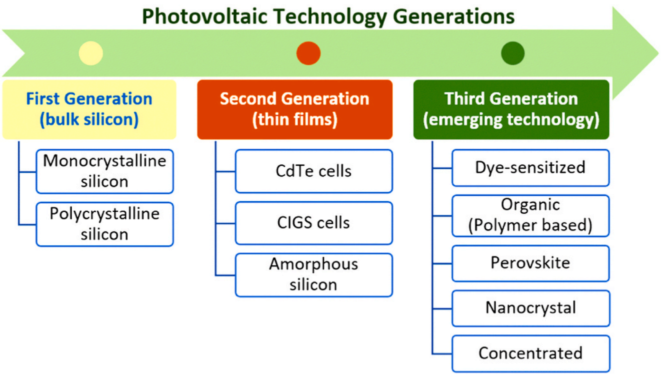


Fig. 2. Classification of PV cell technologies [42].

Crystalline silicon PV technology exhibits high efficiency and energy conversion rates. Silicon atoms absorb photon energy from sunlight that hits silicon wafers. The electrons in silicon flow as an electric current. The arrangement of crystalline silicon PV cells in parallel and series configurations produces the necessary power and voltage output [43]. Around 80 % of solar energy is produced by silicon-based photovoltaic cells, making them one of the most established and conventional technologies for residential and commercial applications. Crystalline silicon PV technology has been steadfast in the solar energy landscape for several decades, showing excellent reliability and efficiency [44]. The use of silicon as a resource for PV cells is advantageous due to its abundance. It is readily available and potentially cheaper [45];

Silicon-based photovoltaic technologies encompass monocrystalline and polycrystalline silicon photovoltaic cells.

2.2.1.1. Mono-crystalline silicon cell. Monocrystalline silicon PV cells are widely used and offer a high conversion efficiency (25 %) among other PV technologies [18,46]. These cells are composed of single crystals of silicon. However, a challenge lies in growing large crystals of pure silicon, contributing to higher manufacturing costs for monocrystalline panels. Over the years, there have been advances in production methods, leading to the low price of panels [47]. Another consideration is that monocrystalline silicon cells are temperature-dependent, experiencing a drop in efficiency as temperatures rise above the Standard Test Conditions (STC) level, set at 25 °C [39].

2.2.1.2. Polycrystalline silicon solar cell. Solar cells made of polycrystalline silicon constitute many crystals, offering a more cost-

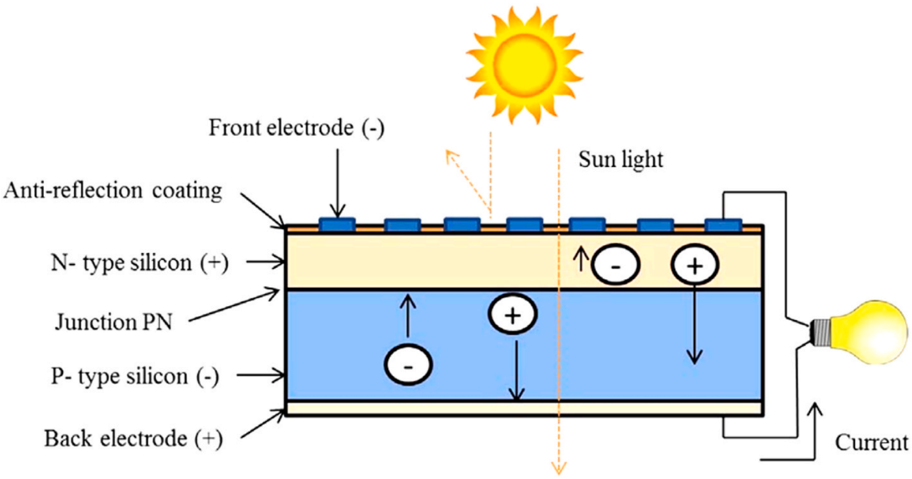


Fig. 1. Schematic p-n junction under load [35].

effective alternative. The production technique involves lowering the temperature of a silicon-molten graphite mold. The process is less costly as it doesn't require closely regulated growing conditions for a single crystal. Polycrystalline silicon solar cells generally have an efficiency of about 15 % [48]. Although polycrystalline silicon PV cells have slightly lower efficiency, their production cost is more economical, unlike the monocrystalline silicon PV cells.

2.2.2. Second-generation PV cell: thin film solar cells

The second-generation PV cells constitute a low-cost thin film, making it preferable to silicon wafer-based first-generation PV cells. The thin film cells of solar cells are significantly thinner than silicon wafers, with a thin light-absorbing layer typically only one micron thick [49]. Materials for this modification extend to amorphous thin film, CdTe, and CIGS [50]. Photovoltaic cells with thin films include.

2.2.2.1. Amorphous thin film PV cell. Amorphous silicon solar cells represent advanced cell technologies constituting p-n or n-p type duality. The p- and n-layers generate an amorphous silicon inner electric field [51]. Amorphous silicon refers to non-crystalline silicon [52]. Manufacturing amorphous silicon cells requires less energy but is more intricate than the crystalline panels, exhibiting lower efficiency, approximately 14 % below the crystalline silicon photovoltaic cells [53]. They are suitable for low-light conditions, providing simplicity of operation.

2.2.2.2. PV cell using Cadmium Telluride. The PV cell illustrates the material layer structure of a CdTe thin-film photovoltaic cell. The substrate for polycrystalline CdTe solar cells is typically glass. The Photovoltaic cells leverage the optical absorption properties of Cadmium Telluride (CdTe) in Group II and VI elements in the periodic table [54]. They exhibit a high absorption factor with energy exceeding the bandgap within a few micrometers of the CdTe absorber plate [55]. However, the cadmium component of CdTe is a hazardous heavy metal that poses environmental and health risks to both humans and animals [56]. Despite these challenges, CdTe photovoltaic cells have witnessed a notable improvement in efficiency compared to the past 17 years. Recent studies report that CdTe-based thin-film solar cells have achieved an efficiency of 20.03 %, a Voc of 0.863 V, an Isc of 29.2 mA, and a fill factor of 79.5 % [55].

2.2.2.3. Other advanced second-generation PV cell technologies: copper indium gallium selenide. CIGS solar cells comprise elements from Periodic Table Groups I, III, and VI, with the chemical formula CuInxGa (1−x) Se_2 [55]. CIGS is valued for its high absorption coefficient and boasts one of the highest current densities among semiconductor materials. Despite its promise, the environmental concerns arising from heavy metals like cadmium, a component of CIGS, need consideration [57].

The following is a list of the benefits of second-generation solar energy systems [55,58].

i. They absorb maximum coefficient;
ii. They use less material, up to a few microns thick, making them less expensive.
iii. This technical innovation can help simplify manufacturing stages by facilitating direct integration with high-voltage modules.
iv. They use vacuum and non-vacuum procedures.

Despite the benefits, there are a few disadvantages.

i. They are less efficient, recording an efficiency of 20 % compared to first-generation solar cells.
ii. The rapid deterioration caused by the light generated limits its use outdoors.

2.2.3. Third-generation photovoltaic cell

The third generation of PV aims to introduce new materials using new techniques, filling the gap left by 1st and 2nd generations of PV cell technology that demanded greater efficiency from devices using thin-film deposition [36]. The more advanced techniques are costlier but with a lower cost per peak watt. The technology is non-toxic and utilizes naturally available resources, hence best suited to applications in larger-scale PV solar cells. The materials can be organic and nano-structure. Utilizing carrier collection promotes a higher efficiency level greater than 60 % [38]. The third generation of photovoltaic cells aids the improvement of charge carrier mechanisms, charge collection, and energy production. The most third-generation PV cell technologies include.

2.2.3.1. Multi-junction (concentrated) PV cell technology. Multi-junction PV cells are advanced solar cell technology, providing high efficiency by utilizing multiple semiconductor wafers with varying band gaps [59]. Each layer optimizes sunlight absorption by capturing a solar spectrum and is essential in concentrated photovoltaic systems and space applications where higher efficiency is crucial. Multi-junction PV cells comprise indium gallium phosphide or gallium arsenide semiconductors. These cells can reach efficiencies greater than 40 %, representing a substantial advancement over traditional silicon-based solar cells, accomplished by stacking multiple layers of different materials, each with varying band gaps [60,61].

2.2.3.2. Dye sensitized PV cell (DSPCs). DSPC technology employs a photoelectrochemical process. It comprises an electrolyte, a counter electrode, and a porous film of nanocrystalline titanium (TiO2) coated with a light-absorbing dye [62]. In a DSPC, the dyes capture photons from sunlight and generate electrons into the TiO_2 layer [63]. These electrons flow through an external circuit, producing an electric current. The electrolyte helps regenerate the dye by accepting electrons from a redox couple, thus completing the cycle [62]. DSPCs provide advantages such as ease of manufacturing, low-cost materials, and the ability to operate under lower light conditions and indirect sunlight. However, they are less efficient than first-generation conventional cells [64].

2.2.3.3. Perovskite PV cell technology. Perovskite photovoltaic (PV) is an emerging technology that has gained considerable interest due to its manufacturing cost-effectiveness and efficiency [65]. PV comprises perovskite materials (methyl ammonium lead iodide) deposited on a substrate to absorb sunlight, creating electron-hole pairs [66]. The high absorption coefficient and tunable band gap of PV cells are great promises in achieving high efficiencies [67]. However, PV cells demonstrate poor stability, scalability, and durability due to their sensitivity to moisture, heat, and UV light, degrading their performance over time [51].

2.2.3.4. Quantum dot (Nanocrystal) PV technology. The active solar cell materials in quantum dot (QD) photovoltaic technology comprise tiny semiconductor particles (quantum dots). Depending on their size, quantum dots capture various portions of the light spectrum [68]. In a quantum dot PV cell, the QD layers occupy the midpoint of the transport layer for electrons and holes. Electron-hole pairs' generation accompanies quantum dots' absorption of photons [69]. The charges created through photo generation produce an electric current. Comparatively, quantum dot solar cells absorb a high spectrum of sunlight due to their tunable band gap, making them particularly promising for applications where spectral matching is essential.

2.2.3.5. Organic photovoltaic cell technology. Organic photovoltaic cell (OPC) technology involves organic semiconductor electronics that use small organic molecules or conductive organic polymers to absorb sunlight and generate charge carriers through the photovoltaic effect

[70]. OPCs comprise conjugated polymers or small organic semiconductor molecules with high optical absorption coefficients and customizable properties through flexible synthesis and low manufacturing costs. Organic PV cells are typically structured using bilayer or bulk heterojunction topologies [71]. The ability to process solutions, effective industrial manufacturing technologies, and high efficiency at high temperatures show the significant benefits of third-generation PV cells. Efficiency improvement and lower manufacturing costs constitute the pressing challenges in this generation.

Table 1 presents the comparative analysis of generation materials for photovoltaic cells in terms of their efficiency, advantages, limitations, manufacturing processes, application, durability, and stability. Table 2 shows the comparative analysis of PV parameters, fill factor, voltage drop, charge density, and efficiency of selected record-breaking solar cells. First-generation material (silicon) recorded 6–25 % efficiencies, while the second and third-generation materials recorded about 10–15 % and more than 20 % efficiencies, respectively.

2.3. *Organic PV cells*

The origins of OPV cells may be found at the beginning of the twentieth century when researchers began investigating the possibilities of utilizing organic materials in solar cells instead of the more conventional inorganic ones. Organic materials like polymers and tiny molecules in organic photovoltaic cells convert sunlight into electricity [81]. In contrast to inorganic materials like silicon, which need intensive mining and processing, These are carbon-based composites manufactured by absorbing light photons and using organic substances [82]. Usually, several layers make up the cells, such as an organic layer positioned between two electrodes. Electrons move from one electrode to another due to light absorption, creating a current [83].

2.3.1. *Overview of related works on organic photovoltaic technology*

Review et al. [84] explored the future of organic photovoltaics, highlighting advancements, challenges, and increased stability and efficiency. The review emphasizes the need for further study in overcoming these limitations and achieving commercial viability, highlighting the need for further advancements in the field. Comparable research by Chatzisideris et al. [85] deduce that organic photovoltaic battery storage systems (PVs) offer lightweight, flexible, and semi-transparent alternatives to silicon-based conventional PVs, making them ideal for business intelligence applications. However, they have reduced power conversion efficiency and shorter lifespan compared to traditional PV technology. Another similar study by dos Reis Benatto et al. [86] examined the lifecycle of a solar charger with an integrated organic photovoltaic system, focusing on its commercial application and environmental impact, as well as its recycling and disposal stages.

Table 1
Comparative assessment of first, second and third generation PV cell technology [29,72–74].

	First-generation	Second-generation	Third-generation
Construction materials	c-Si	Amorphous thin film, CIGS, CdTe	organic materials, GaAs, perovskite materials, nanocrystal
Range of efficiency	25 %	10–15 %	20 %
Benefits	Track record technology, efficiency gains	Lightweight, flexible, roll-to-roll, low cost	Lower-cost materials, possible major cost reductions in solar energy, increased efficiency
Restrictions	Costly to produce, loss of efficiency at higher temperature	Long-term stability and durability, low efficiency	It is currently researched and developed stage
Fabrication Process	Wafer based	Roll-to-roll	Varies according to the material and the design
Application areas	Projects in the residential, commercial and utility sectors	BIPV, handheld and light weight solar modules, small scale project	Large installations, home appliances, stand-alone installations
Durability	Highly durable	moderately	Differ according to material and designed
Stability	Highly stable	moderately	Differ according to material and designed
life time (yrs)	30	15–20	10–15

Table 2
Comparison of PV parameters, voltage drop, charge density, fill factor, and efficiency of selected record-breaking solar cells.

Classification	$V_{OC,}$ V	JSC, mA cm^{-2}	FF, %	PCE, %	Reference
c-Si	0.74	42.6	84.9	26.7	[75]
a-Si	0.89	16.36	69.8	11.9	[76]
GaAs	1.12	29.8	86.7	29.1	[77]
CdTe	0.89	31.69	78.9	22.3	[78]
CIGS	0.73	39.4	80.4	23.4	[78]
lnP	0.939	31.15	82.6	24.2	[79]
Perovskite	1.19	26.4	81.7	25.6	[78]
Perovskite-/Si	1.974	20.99	81.3	33.7	[26]
Perovskite/ perovskite	2.15	16.51	81.7	29.1	[80]
Organic	0.89	26.7	80.8	19.2	[26]
Perovskite/organic	2.14	14.56	75.6	23.6	[77]

Cutting et al. [87] study found that organic photovoltaic cells perform better under LED light than inorganic Si cells. PCEs of crystalline and amorphous Si solar cells exhibit an increase of around 20 % under LED illumination. P3HT device showed the most PCE gain of 300 % under light, possibly due to spectrum compatibility with the photoactive material's absorption. Light intensity also significantly impacted the performance of the crystalline silicon. The study suggests that OPVs significantly enhance their PCEs under LED illumination. Yu et al. [88] explored the impact of Al-doped zinc oxide nanostructure on organic solar cell efficiency. The high transparency in the visible spectrum of zinc oxide thin films from sol-gel has gained interest. The active layer contains P3HT: PCBM. Incorporating aluminium increased the grain size. Solar cells with a ZnO/AZO (0.5:1 %) ratio show enhancement of PCE, similar to those without aluminum doping.

Jannat et al. [89] analyzed organic photovoltaic cells, focusing on their materials, structure, stability, working principles, challenges, potential, and applications. The process involves creating a photocurrent, which disperses to the donor-acceptor interface and carries charges to electrodes. Key components include electrodes, electrons, hole transport layers, and the active layer. Organic photovoltaic cells are lightweight, easy to manufacture, and cost-efficient but exhibit poor power conversion efficiency, stability, degradation, lifetime, and scalability. Similarly, Duan and Uddin [90] review of the stability of OPV cells explores the challenges of maintaining stability, including external conditions and degradation mechanisms. The authors discuss methods to improve stability, such as stable materials, interface engineering, and encapsulation techniques. They emphasize understanding degradation mechanisms and factors like moisture, oxygen, and light. The paper also discusses characterization techniques for assessing stability, including accelerated aging, lifetime measurements, and stability modeling. The study comprehensively analyzed the advancements in enhancing organic solar cell stability and suggested potential future research areas. Another study by Status et al. [91] explored the potential of small molecules as components in developing efficient and scalable organic photovoltaic systems. The research highlighted the significance of molecular design and structure-property relationships in enhancing performance and the advantages of using vacuum processing techniques in organic solar cell fabrication. The study also examines prospects and challenges in this domain.

The discovery of organic photoactive components, particularly non-fullerene electron acceptors, has advanced photovoltaic (OPV) cells. Top-performing OPV cells have power conversion efficiencies exceeding 16 %, but large-area manufacturing is not feasible due to spin-coating processes. Modifying flexible side chains of non-fullerene acceptors achieves 17 % PCE, and spin-coated devices can retain high efficiencies even with scaled blade-coating techniques. Enhancing OPV materials' chemical constituents improves device performance for larger-scale manufacturing and commercialization [92]. A related review by Ajay et al. [93] evaluated the knowledge of OSCs, highlighting their prospect for commercialization and increased efficiency. With over 20 % efficiency, NFAs have renewed OPV development. Novel device designs, such as tandem and ternary, are discussed. The study reviewed efficient devices and explored tactics for achieving state-of-the-art OSCs. It also addresses crucial problems facing OSCs.Similarly, Gao et al. [94] conducted a review on organic photovoltaic (OPV) progress, revealing that non-fullerene narrow band gap materials like Y6 or their derivatives enhance the performance of OPV cells by over 18 % when used as electron acceptors.

Tyona [95] presents an in-depth theory of the spin coating technique, detailing the fundamental principles and parameters that govern the process. The theory describes four main stages: deposition, substrate acceleration, spinning at a constant speed where fluid viscous forces dominate, and solvent evaporation. It also discusses common thin film defects such as comets, chuck marks, environmental sensitivity, and edge effects. Spin-coating polymers in volatile solvents produce a uniform and thin surface layer, typically a few hundred nanometers thick, essential in applications like organic photovoltaic cells and electronic devices [96]. Organic materials produced in relatively small quantities (around 100 nm thick films) are easily manufactured on a large scale, unlike inorganic materials, requiring more complex growth processes [97]. A prestigious research institute is the National Renewable Energy Laboratory, which focuses on energy performance and alternative energy sources, providing valuable data on the advancement of OPV cell technology [98]. Comparatively, inorganic photovoltaic (IPV) cells show better efficiency, stability, and strength than organic photovoltaic cells [99].

Table 3 depicts the summary of related works on organic photovoltaic technology. The review highlights that while OPV cells have reached PCEs exceeding 19 %, the efficiency is still lower than the traditional inorganic photovoltaic (IPV) cells. This limitation in efficiency limits the commercial viability and widespread adoption of OPV technology. The review highlights the importance of spin-coating and other vacuum-based processing techniques for OPV manufacturing. However, these methods may not be suitable for large-scale production. Research is needed to explore alternative, more scalable, cost-effective manufacturing processes for OPV cells. The review highlights that OPV cells face challenges in maintaining stability and have shorter lifespans than the traditional silicon-based photovoltaic technology. Further understanding of the deterioration mechanism and strategies for improving the OPV cell's performances and operational lifetime remains paramount.

Given the literature review, it became apparent that there is a critical need to address the stability and efficiency of OPVs to ascertain their potential in practical applications. This review article aimed to conduct a comprehensive review by providing an updated overview of the advancements and challenges in OPV technology and emphasizing the need for further study in the field. By synthesizing the existing literature and presenting the current state of OPVs, this review article sought to inform researchers and industry professionals about the areas that require more attention and investment to make OPVs a more viable and competitive alternative to traditional photovoltaic technologies.

Table 3
Summary of related works on organic photovoltaic technology.

S/N	Insight	Method	Findings	Ref
1.	OPV cell efficiency is significantly improved by optimizing intermolecular packing and charge transport through the conformation of solid additives.	Design and synthesis of volatilizable solid additives (SADs)	The Planar SAD achieves a record-breaking 18.85 % efficiency to convert power.	[100]
2.	The use of a nitroxide radical conjugated polymer additive improves NFA-OSCs efficiency by enhancing VOC, FF, and JSC, addressing challenges in organic photovoltaic cells.	Application of a novel conjugated nitroxide radical polymer	Improved photovoltaic performance of NFA-OSCs from 15.8 % to 18.3 %.	[101]
3.	The organic photovoltaic cell in the study achieved 17 % efficiency by optimizing non-fullerene electron acceptors, showing promise for high efficiency and scalable production, addressing current challenges in OPV technology.	Spin-coating method, Scalable blade-coating processing technology	NFAs with modified side chains achieve 17 % PCE in OPV cells. Blade-coating maintains high efficiencies for scalable production of OPV cells.	[102]
4.	The efficiency of OSC is enhanced to 19 % by optimizing material design and blending strategies, showcasing potential for broader applications with improved power conversion efficiency.	Material Design with Ternary Mixing Strategy	Material design and ternary mixing strategy improve PCE. Single-junction OPV cells achieve 19.0 % PCE.	[103]
5.	OSC efficiency can reach 18.80 % by lowering nonradiative losses and optimizing active layer morphology, revealing a promising perspective with OPV challenges.	Suppressed non-radiative energy loss -Tuned active layer morphology	Organic solar cell efficiency of 18.80 % has been achieved.	[104]

2.4. Device operating principles

Organic semiconductors possess distinct fundamental characteristics compared to their inorganic counterparts, leading to different operational mechanisms in OPV cells versus inorganic PV cells [105]. Consequently, OPV cells comprise conjugated polymers, small molecules, and organic semiconductors. Photovoltaics refer to the process of converting light into electricity [106].

2.4.1. The photovoltaic process

The technique of photovoltaic process used in OPV is different from that used in inorganic photovoltaic because inorganic materials allow light with greater energy levels than the band gap to be directly absorbed and generate free energy carriers that can separate at a p-n junction and subsequently spread to the corresponding electrodes by an externally supplied electrical current [107]. Conversely, natural substances often exhibit a dielectric value that is significantly lower than that of their conventional opponents, which hinders the assessment of the columbic interaction between holes and electrons, forming exactions or electron-hole pairs bonded by columbic forces during photo-absorption [108]. The excitons require separation into free-charge pairs before being utilized in an external circuit. Throughout its lifespan, the exciton will gradually return to its baseline condition if it is unwilling to dissociate, losing the energy it has received. Similarly to a p-n junction, exciton dissociation in OPVs depends on the presence of two-component units (an electron donor and acceptor). During photo-absorption, exactions or coulombically linked electron-hole pairs occur instead of free carrier charges when the electron donor constitutes a high magnitude of electron value [89].

Fig. 3 shows the simplified energy level of organic solar photovoltaics (OPV). The ionization potential for an impartial molecule of organic matter is the amount of energy required to eject an electron from its HOMO and put it in a vacuum. The LUMO level of an organic matter in a vacuum helps to estimate the electron affinity, indicating the ability of a material to accept electrons. The least amount of energy necessary for the transfer of an electron from the HOMO to the LUMO in a conjugated organic material is known as the HOMO-LUMO gap or band gap [84,109].

Fig. 4 demonstrates typical operations for the organic photovoltaic cell anode and cathode materials having a focus on energy discrepancies among acceptor and donor HOMO (ΔIP) and LUMO (ΔEA) levels. Understanding these differences is essential to understanding charge transport pathways.

Step 1: It is possible to stimulate an electron from the donor HOMO to its LUMO, which results in the development of an exciton that needs to diffuse via a chemical potential gradient to a donor/acceptor interface to absorb sunlight and produce electricity [109].

Step 2: Exciton diffusion is the process through which an electron can move from the donor LUMO to the acceptor LUMO of the material of interest, generating charge transfer (CT) complexes. This occurs where the difference in energy (ΔEA) among the donor and acceptor LUMOs is higher than the binding energy (EA) of the excipient, a variety of the substances used; in most instances, this energy differential is only a few hundred meV [110]. Any energy received in these systems via this energy of exciton bonding is considered waste. The distinction between donating LUMO and accepting HOMO, to a certain extent, determines the theoretical greatest achievable voltage output of these cells, constituting a significant concern in the engineering of the components [111]. The energy of the charge transport state strongly depends on the type of electric charge carriers' Columbic desire and, consequently, on the distance separating these species. The outcome represents the charge carriers bound together via coulombic forces within a donor/-acceptor pair. In other words, the charge transport state can become a free carrier or a charge-separated state.

Step 3: If the separation between the holes and electrons is more than the coulomb capture radius, charge transfer will occur during the photovoltaic process, which is competitive with the production of free charge carriers and represents an additional degradation process in such devices, occurs when the geminate pair is incapable of escaping the Coulomb trap radius and recombines at the donor/acceptor interface [108], indicating that dissociation charges transfer to the electrode via p-type or n-type regions. The anode and the cathode constitute the collection points for holes and electrons [112].

Step 4: Energy utilized to power an outside circuit consists of accumulated charges. Charge recombination - the process by which free and unbound carriers reunite within the device - is OPVs' final and most significant loss mechanism. Charge transfer to the electrodes directly competes with this mechanism [113]. Organic photovoltaic systems aim to minimize energy use as one of their primary objectives and charge dissipation processes to boost device performance.

2.4.2. *Comparison of the operational philosophy of organic photovoltaics and traditional crystalline silicon-based photovoltaics in term of electron-hole pairing and light trapping principles*

The operational principles of Organic Photovoltaics (OPVs) differ significantly from those of traditional crystalline silicon-based photovoltaics, especially in terms of electron-hole pairing and light-trapping mechanisms. Understanding these differences is crucial for advancing the efficiency and applicability of OPVs. In this context, we delved into the comparative analysis of electron-hole pairing and light trapping principles in OPVs and crystalline silicon-based photovoltaics.

OPVs are thin-film, flexible solar cells that employ organic semiconducting materials to convert sunlight into electricity [114]. In OPVs, the mechanism of electron-hole pair generation depends solely on the exciton dissociation process. Excitons, bound electron-hole pairs, are created when photons strike the organic semiconductor layer in an OPV, dissociating at a donor-acceptor interface, where electrons transfer to an acceptor material, and holes remain in a donor material. The result of this process is the production of free charge carriers at the electrodes for electrical current generation [115,116]. Traditional crystalline silicon-based photovoltaics, on the other hand, work by generating free charge carriers directly. Photons interact with the silicon crystal lattice, forming electron-hole pairs immediately through the material, owing to the bandgap of silicon, which allows for the effective production of free carriers during photon absorption [117]. Comparatively, OPVs rely on the dissociation of excitons, an inherently different mechanism from the direct generation of free carriers in crystalline silicon-based photovoltaics. The exciton dissociation process presents both advantages and challenges for OPVs. It allows for the use of lightweight and flexible

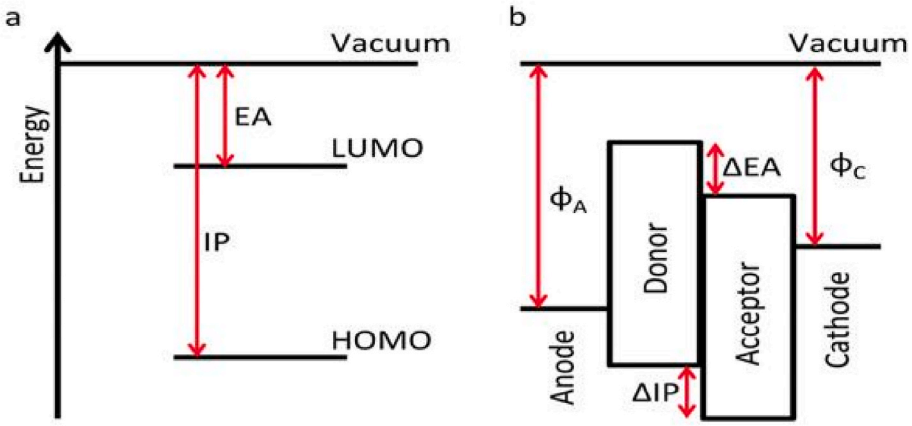


Fig. 3. Basic energy level diagrams of (a) organic semiconductor and (b) hetero-junction solar cell.

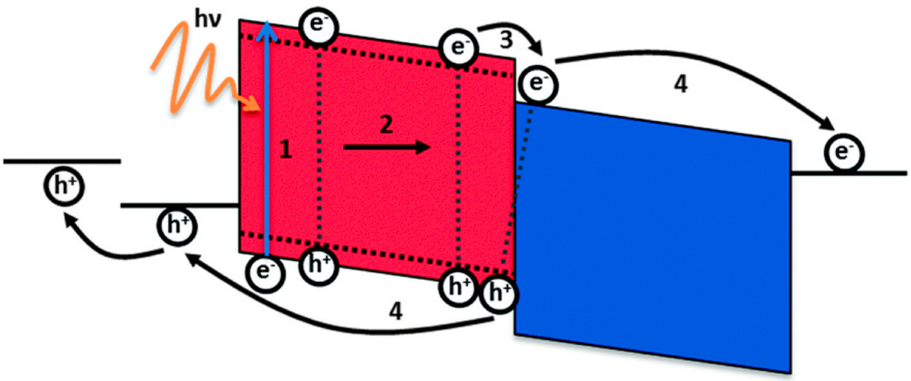


Fig. 4. OPV working principle, donor (left side) and acceptor (right side) [84].

organic materials, allowing the development of inexpensive and flexible PV cells [116,118]. Even so, improving the effectiveness of dissociation and carrier transport in OPV is an ongoing subject of study to continue to enhance the overall performance of PV cells.

Concepts of light trapping in OPVs and Crystalline Silicon-based PV Systems describe the tendency for solar cells to capture and absorb light in the active semiconductor layer, thereby extending the optical pathway and increasing light absorption. In OPVs, textured or patterned surfaces, nanostructures, or optical coatings induce light trapping. These techniques aim to maximize light capture within the thin organic layers of the solar cell, enhancing photon absorption, exciton generation, and power conversion efficiencies [119]. Conversely, traditional crystalline silicon-based photovoltaics utilize light-trapping mechanisms such as surface texturing, anti-reflective coatings, and backside reflectors to enhance light absorption [120]. These techniques are employed to minimize reflection and maximize the absorption of incident sunlight within the thick silicon wafer. Additionally, silicon solar cells can incorporate light-trapping structures such as pyramid textures or diffraction gratings to efficiently trap light and optimize light absorption in the silicon material [121].

2.5. Device structure of OPV cells

2.5.1. Single layer OPV cells

Fig. 5 depicts the most basic OPVs, consisting of one organic layer with an effective light-harvesting and electricity-generating mechanism. Single-layer OPV cells exhibit lower performance than other cell types [122]. Given the donor and acceptor material in one layer in single-layer OPV cells, the device structure may be simplified, possibly resulting in cheaper costs for manufacturing [123]. The emitted electron and hole recollect at the electrodes to deliver an electrical current for the electricity supply of external appliances [114,124,125].

2.5.2. Bilayer OPV cell

A form of thin-film PV cells known as a bilayer OPV consists of two organic semiconductor layers, usually the n-type (electron-accepting layer) and a p-type or electron-donating layer, placed between a pair of electrodes. When bilayer OPVs are present, the p-type typically consists of a tiny molecule or conjugated polymer exhibiting a low ionization capacity, and the n-type layer is generally a high electron affinity non-fullerene acceptor or a fullerene derivative [126,127]. Solution-based approaches like spin coating techniques constitute the basic layer deposition technique. Sunlight striking the bilayer cell causes an exciton to form a donor-electron layer, which splits into an electron and holes. The positive electrode and the electron acceptor layer receive the existing electron and hole, respectively [128].

2.5.3. Heterojunction OPVs cell

OPVs are a family of thin-film PV cells composed of an assembled heterojunction of donor and acceptor materials. The materials of the donor and the acceptor are typically blended conjugate polymers or small molecules in solution and spin-coated or applied by other solution-based techniques [129,130]. The mixture forms an intermediate layer between the donor and acceptor materials, facilitating the separation of charge and transport. The electron donor and acceptor are placed between the anode and cathode or the two electrodes [29]. An exciton is created in the electron donor material when solar light hits the OPV bulk heterojunction cell, indicating electron transport to an electron-accepting material [124,131].

2.5.4. Tandem OPV cells

Tandemised PV cells consist of two or more series-connected cells to

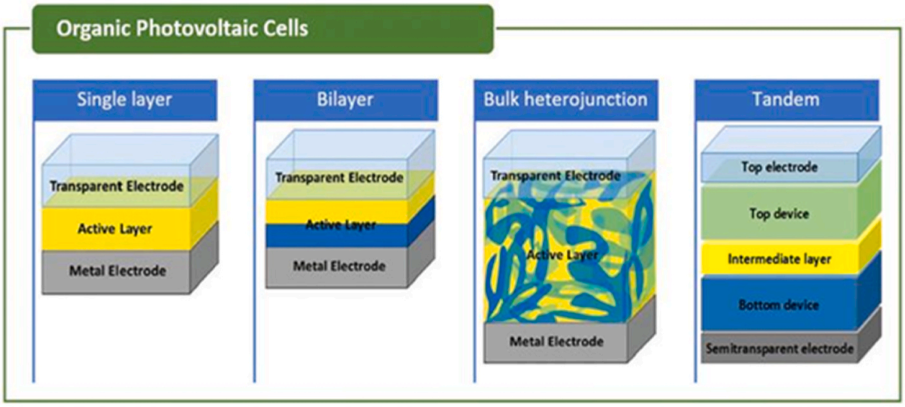


Fig. 5. OPV cell device structure.

boost efficiency. The subcells constitute a variety of materials with several different band gaps for the absorption of spectral regions of the light spectrum. Each tandem PV cell has one absorbing material and one electron-transporting material [132]. Excitons or electron-hole pairs occur through the absorption of incoming photons by the absorber material and the movement of the resultant charge carriers by the electron transport material [133,134]. The first sub-cell accepts high-energy photons and low-energy photons [29]. A great range of solar spectra induces absorption and conversion into electricity. Tandem photovoltaic (PV) cells can increase a solar cell's efficiency. Table 4 depicts the summary comparison of OPV cell device structures.

2.6. *Organic photovoltaic cells: advantages and disadvantages*

There are several advantages for specialists, producers, and customers of organic photovoltaic cells. As technology improves, there should be a substantial increase in the advantages of OPVs.

The benefits of OPV cells are as follows:

i. Modular and low-weight designs are substantially more durable and have a greater coverage area than typical solar and organic PV cells [71].
ii. Cheap production cost: Because organic molecules are soluble, roll-to-roll systems preferably surpass other costly, less ecologically harmful techniques [130,135].
iii. Resource abundance: The raw ingredients needed to create organic solar cells are widely available [136].
iv. Eco-friendly: Comparatively, organic PV cells have eco-friendly [71].

2.7. *Drawbacks of solar cells made on organic matter*

Comparing organic solar cells to silicon photovoltaic cells, research and development on the former is still in its infancy. As a result, there are unanswered questions regarding organic cells.

The disadvantages of organic solar cells are as follows:

i. Efficiency: Comparatively, silicon cell OPVs has far lower cell efficiencies.
ii. Lifespan: Silicon cell OPVs have a much shorter lifetime because organic materials deteriorate far more quickly when subjected to environmental factors.

3. Prospects of organic photovoltaics

3.1. *Application of organic photovoltaic*

Organic PV cells offer diverse and promising applications, with one notable use being building-integrated photovoltaics (BIPV). BIPV involves seamlessly incorporating solar panels into the architectural design and generating electricity as an integral part of the building envelope. The flexibility and lightweight of OPV cells enable their easy integration into building materials for BIPV applications, contributing to sustainable architecture by reducing energy consumption [137]. Another promising application of OPV technology is in portable electronics and wearable devices. Due to their flexibility and lightweight nature, OPV cells are an ideal power source for devices that require portability or wearable functionality [138]. For example, OPV cells can be easily integrated into clothing, backpacks, or other accessories, providing a renewable power source for charging mobile devices or powering small electronics [139]. This application could be valuable in remote areas with limited access to conventional power sources. Additionally, OPV technology shows its usefulness in consumer electronics and automotive applications. As the efficiency and durability of OPV cells improve, they could be seamlessly incorporated into products like smartphones, tablets, and e-readers, offering a renewable energy source for these devices. Furthermore, OPV cells could be integrated into electric vehicle designs, helping to extend their range and reduce reliance on traditional charging infrastructure.

3.2. *Environmental benefit of traditional PV technology*

OPV cells offer eco-friendly benefits compared to traditional PV technology. Due to their lightweight, cost-effectiveness, and flexibility, OPV cells hold significant promise in the energy sector [140]. These cells exhibit low material toxicity, resulting in a reduced environmental impact compared to traditional PV technologies [141]. OPVs typically require less energy than silicon-based PV cells. Silicon solar cell manufacturing involves high-temperature processing, unlike OPVs manufactured at lower temperatures using roll-to-roll processes, resulting in lower energy consumption [142]. The manufacturing of OPVs constitutes the use of organic polymers. OPVs showed a lower carbon footprint than the silicon materials used in traditional PV technologies [137,143].

3.3. *Industrial interest in organic photovoltaic*

Many businesses have started researching the development of OPVs

Table 4
Summary comparison of OPV cell device structures.

Structure	Advantages	Disadvantages	Main characteristics
Single layer	• Single unit Architecture • Easy to fabricate	• Poor charge carrier mobility • Limited light absorption due to the thin active layer • Lower efficiency	A single organic coating that is a composite of both donor and acceptor compounds, for a total of three layers.
Bi-layer	• Improved charge separation due to the heterojunction interface • Better light absorption compared to single-layer architecture • Greater efficiency compared to single layer OPV	• relatively low Carrier mobility • Diffusion of excitons Length restricts active layer thickness • Complicated device structure than single layer OPV	Solution-based processes such as spin-coating, which involves sandwiching organic semiconductor layers between two electrodes.
Bulk hetero-junction	• Efficient exciton dissociation due to large interfacial area • Improved charge mobility compared to bilayer • Great efficiency and superior flexibility.	• Achieving optimum performance through complex mixing of donor and acceptor materials. • Potential for bi-molecular recombination losses	Interpenetrating network of electron donor and electron acceptor materials. Typically deposited by spin coating.
tandem	• Increased light absorption through the use of multiple active layers • Higher efficiency by stacking sub-cells with complementary absorption spectra	• More complex device architecture in terms of fabrication and charge transport. • Potential current-matching issues between the sub-cells	For absorption of various bands of the light spectrum, a series of two or more sub cells, each with a different band gap, is used.

devices to bring them to market, motivated by recent advancements in the efficiency of OPVs cell and the financial advantages of processing and manufacturing organics.

Brabec et al. [144] established in their study on the potential for high-volume industrial production of OPV modules that solutions-based methods are suitable for the deposition of organic thin films under atmospheric conditions, such as ink-jet printing. Kim et al. [145] demonstrated the potential of low-cost, scalable OPV units manufactured with non-halogenated solvents, significantly reducing manufacturing costs without compromising device performance. The study also highlighted the cost-effectiveness and scalability benefits of OPV technology. The scalability and low-cost approach could change the solar cell fabrication paradigm and enable new markets based on low-cost PV with modest efficiencies and lifetime. Low manufacturing costs and lightweight construction are crucial factors influencing the cost-effectiveness and scalability of Organic Photovoltaic technology compared to traditional photovoltaic systems. The low manufacturing costs of OPV accompany the use of abundant organic materials, roll-to-roll printing processes, and solution-based deposition techniques, which require less energy and are less costly than the complex, high-temperature processes required for traditional silicon-based PV modules [146,147]. In addition, the inherent lightweight nature of OPVs, realized by thin, flexible substrates, allows for easy integration into diverse uses such as BIPVs, portable electronics, and even wearable technology [28]. This lightweight and flexible nature makes OPVs easier to transport, handle, and install. It also opens up new opportunities for unconventional and creative applications, ultimately contributing to the cost-effectiveness and scalability of the technology [29].

Despite the advantages, OPV production processes exhibit some environmental concerns that maximize their ecological footprint. One of the main environmental impacts of OPV production is the use of solvents and chemicals in the manufacturing process. These solvents and chemicals can be toxic and harmful to the environment if not handled properly. Additionally, the disposal of these chemicals can lead to pollution of water sources and soil [148,149]. Another environmental concern with OPV production is the energy consumption associated with manufacturing and processing the materials used to make solar cells. Although OPVs are potentially more energy-efficient than conventional silicon-based solar panels, the production process still requires energy for heating, drying, and other manufacturing steps [150]. Minimization of the ecological footprint of OPV production methods requires overcoming several obstacles. One of the key challenges is developing more sustainable and environmentally friendly solvents and chemicals for the manufacturing process, including organic semiconductors, metal-free materials, and biodegradable and recyclable encapsulation materials [151,152]. Another solution is developing effective recycling processes for OPVs to minimize their environmental impact, aiding disposal and recycling end-of-life OPV modules crucial in reducing their ecological footprint [152].

3.4. Factors influencing overall efficiency of organic photovoltaic cells

Efficiency is not the only factor that determines the value of PV technology. Given the balance of systems and the associated soft costs of photovoltaic installation, maintaining a certain minimum efficiency level is crucial. The real challenge for OPV lies in scaling up the impressive efficiency gains achieved in lab-scale devices to larger module-scale applications [139]. In recent years, research reported efficiencies as high as 20 % [153,154]. Fig. 6 shows the lists of efficiency for various PV cell types [155].

Despite their advantages, OPVs have not yet achieved the higher efficiencies needed to compete with crystalline PV cells, which reach around 25 %, needing further improvements. The photovoltaic cell performance and electrical features are critical in the determination of the efficiency of OPV cells. Measuring its cell performance using several characteristics such as power output, efficiency, and fill factor [156,157].

i. A solar cell's greater electrical output under typical test conditions is its output power. When a PV cell is efficient, its efficiency is as presented in Equation (1):

$$\eta = \frac{P_{out}}{P_{in}} \tag{1}$$

ii. The relationship between the maximum output power per watt and the product of V_{OC} and I_{SC} of a photovoltaic cell is called the FF, as shown in Equation (2).

$$FF = \frac{P_{max}}{V_{OC} x I_{SC}} \tag{2}$$

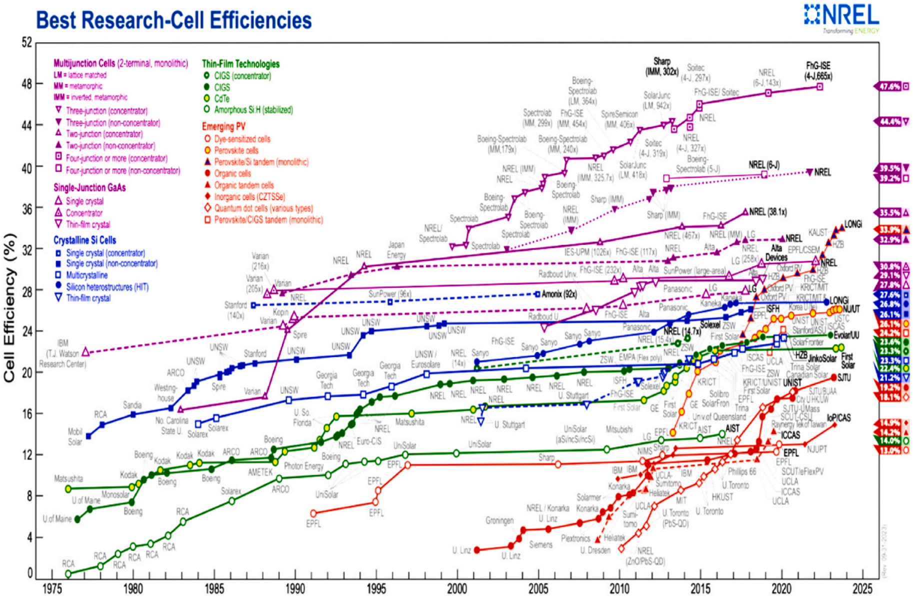


Fig. 6. **The recent chart for the efficiency of research cells** [155].

iii. For PV cells, efficiency is the most essential metric. The phrase PCE presented in Equation (3) shows how well a device converts solar energy into electrical energy.

$$\mathbf{PCE} = \frac{\mathbf{V_{oc}\ x\ J_{SC}\ x\ FF}}{\mathbf{P_{in}}} \tag{3}$$

3.4.1. Performance metric, limitation, and way forward

3.4.1.1. Fill factor (FF). A higher FF value indicates that the PV cell delivers power close to the theoretical maximum, which is desirable for achieving high PCE [158]. However, the fill factor in OPV cells is typically lower than in silicon-based solar cells due to non-ideal charge transport, recombination, and series resistance [159,160]. Improving the FF is a crucial strategy for boosting the efficiency of OPV technology.

Way forward.

i. Charge carrier mobility improvement: Improving carrier mobility within the organic materials of the OPV cell reduces recombination losses and increases the fill factor [161]. Developing new organic materials and optimizing film processing conditions can enhance charge transport properties.
ii. Device architecture: Exploration of tandem or multi-junction OPV cells can also contribute to a better fill factor [162]. Stacking multiple active layers with high absorbance of the various regions of the solar spectrum can boost the fill factor of organic PV [163].

3.4.1.2. Open circuit voltage. The no-load voltage indicates the highest solar cell voltage without current. It is driven primarily by the gap created in the active layer of the solar cell between the energy levels of the donor material and the acceptor material [164]. A is desirable to help achieve higher converting efficiencies. However, in OPVs, they are still lower due to the inherently different energy levels in organic semiconductors.

Way forward.

i. Development of new organic semiconductor materials with appropriate band gaps and retaining a sufficiently large driving force for efficient charge separation at the donor-acceptor interface. Materials with optimized energy levels are crucial to maximize the Voc without compromising the charge extraction and transport processes [165].
ii. Optimization of the donor-acceptor interface to minimize energy level offsets and recombination losses while at the same time maintaining sufficient driving force for efficient charge separation and transport [166].

3.4.1.3. Short circuit current density. The Jsc represents the maximum current generated by the PV cell when illuminated and is directly related to the device's ability to absorb light and collect charge [163]. A higher Jsc indicates more efficient light harvesting and charge transport, both essential for achieving high PCE. However, limitations in Jsc can stem from insufficient light absorption, poor exciton dissociation, and inefficient charge transport and collection.

Way forward.

i. Improving light absorption through a new donor and acceptor materials with broader and stronger absorption across the solar spectrum can increase the number of photons absorbed and contribute to higher Jsc through molecular design, creating low bandgap materials, or employing tandem cell architectures [163].
ii. Optimizing the donor-acceptor interface for efficient exciton dissociation by controlling the morphology to facilitate efficient exciton separation into free charge carriers is crucial. Techniques like controlled annealing or the addition of interfacial layers can improve exciton dissociation and charge extraction [167].
iii. Improving charge transport and collection by high-mobility organic semiconductors, suitable charge transport layers, and effective charge extraction mechanisms leading to higher Jsc [167]. Carefully engineering the active layer composition and thickness can also improve charge transport.

Apart from the above-stated attributes, another crucial factor is the temperature coefficient of photovoltaic cells. This coefficient describes how the cell performs differently in response to temperature variations. Temperature varies inversely with the performance [140]. The efficiency of OPV cells is strongly dependent on their operating temperature. As the temperature of OPV cells increases, their power conversion efficiency (PCE) generally decreases [168]. However, several methods are reportedly diminishing temperature effects. Table 5 shows the different temperature control methods of PV modules. Combined techniques could promote a higher performance of PV cells, especially during the hottest months.

The technology of OPV cells has advanced recently, according to Liet al. [174] and Yao et al. [175] demonstrated FF% of over 80 % and PCE of up to 18.6 %. The results reported by NREL's investigation revealed that FF values ranged from 54 % to 81.5 % and power conversion efficiency from 5.72 % to 18.6 %. The two lowest numbers are 5.72 % and 54 %. The fill factor is a crucial metric that assesses how well a solar cell converts the incident light into electrical energy. Greater output power indicates the device's ability to capture large portions of the current produced. Table 6 shows some recent studies of single-junction and tandem OSCs active Layers with higher efficiency. Fig. 7 shows some donor and acceptor chemical formulae quoted in this review. There is a correlation between FF and PCE of OPV cells. A higher FF implies that more incoming sunlight is converted to electrical energy, enhancing overall efficiency. A compromise exists between FF and PCE since the improvement of one may result in the deterioration of the other. For example, reducing the PV cell's resistance can promote the recombination rate of charge carriers, reducing overall efficiency. Similarly, improving charge carrier collection can increase dark current, reducing fill factor. The optimal balance depends on the solar cell's design and operating conditions and requires careful optimization.

4. Challenges of organic photovoltaic

Several challenges hinder the widespread application of organic photovoltaic.

Table 5
Different temperature control methods of PV module.

Method	Description	reference
Direct spraying:	Spray water directly on PV modules through sprinklers during extreme weather	[169].
Mounting Fins	By attaching fins to the OPV module, heat is efficiently transferred away from the module, thereby reducing the temperature and minimizing the impact on device performance	[170]
Phase change material application	Phase-change materials act as latent heat stores, capable of absorbing excess heat and undergoing solid-liquid transitions at certain temperatures, regulating a PV cell's temperature.	[171]
using high thermal conductivity materials	the use of high thermal conductivity materials, which enhance the dissipation of heat from the PV module, reducing temperature-related performance losses	[172].
Thermoelectric coolers	Thermoelectric cooling is a cooling technique that utilizes the Peltier effect, using electric current to create a temperature gradient for heating or cooling.	[173]

Table 6
PCEs of single-junction and tandem OSCs.

Active Layer	V_{OC} (V)	J_{SC} (mA. cm^{-2})	FF (%)	PCE (%)	Reference
PM6:BTP-4Cl-12[a]	0.858	25.60	77.60	17.00	[102]
PM6:Y6[a]	0.847	25.89	78.59	17.23	[175]
PM6:BTP-eC9[a]	0.841	26.20	78.30	17.80	[176]
PM6:Y6:C8-DTC[a]	0.873	26.50	75.61	17.52	[177]
PBQx-TF:eC9-2Cl:F-BTA3[a]	0.879	26.7	80.90	19.0	[103]
D18:Y6[a]	0.859	27.70	76.6	18.22	[178]
PTQ10:BTP-Ph:BTP-Th[a]	0.888	25.2	78.6	17.6	[179]
PM6:PM7-Si:BTP-eC9[a]	0.866	27.18	80.1	18.9	[178]
PM6:D18:L8-BO[a]	0.896	26.7	81.9	19.6	[79]
PBDB-TF:ITCC/PBDB-TF:BTP-eC9[b]	1.910	14.21	72.37	19.64	[79]
PBDB-TF:GS-ISO/PBDB-TF:BTP-eC9[b]	2.01	13.14	76.75	20.27	[180]

[a] Single-junction OSCs.
[b] Tandem OSCs.

4.1. The challenge of degradation and stability

High efficiency and stability are critical for the commercial success of PVs, particularly in organic matter such as organic conjugates or small molecule polymers. High efficiency and stability demonstrate the commercial success of photovoltaic devices, especially in organically bound materials like organic conjugated polymer [37]. Degradation mechanisms can be physical or chemical and can be intrinsic or extrinsic. Intrinsic degradation occurs due to material alternations (mechanical degradation) and the thermal properties of the materials in the active layer, while environmental conditions (moisture, oxygen, and sunlight) control the extrinsic deterioration [181,182]. Fig. 8 shows the degradation factors that have an impact on the stability of OPV [183].

4.1.1. Intrinsic degradation

Intrinsic degradation in organic solar cells accompanies the thermal diffusion of constituent materials at interfaces, which can occur due to internal modifications or exposure to light or elevated temperatures. These degradations may involve inter-electrode diffusion, interfacial layer deposition, phase separation at the organic cathodic interfaces, and alterations in the nanoscale composition of the bulk heterojunction components [184]. In addition, thermal-initiated Phase Separation and photo-chemical damage occur in the bulk heterojunction films, leading to additional degradation in mechanical features like brittleness and hardness in the photoactive layer [185]. The photoactive layer constitutes the most essential part of OPVs. It exhibits a metastable phase transition due to its high mobility. Additive solvents with a high boiling point enhance their performance but severely affect the stability of the

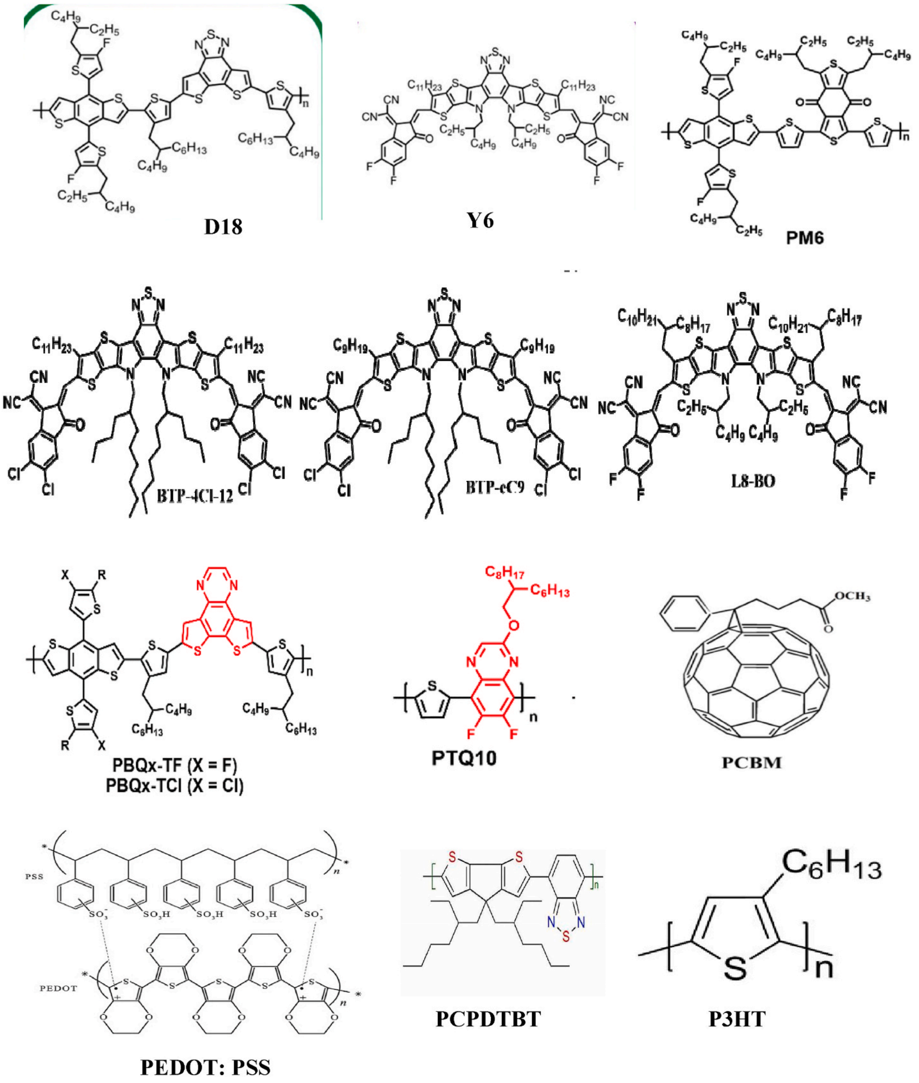


Fig. 7. Some donor and acceptor chemical formulae quoted in this review.

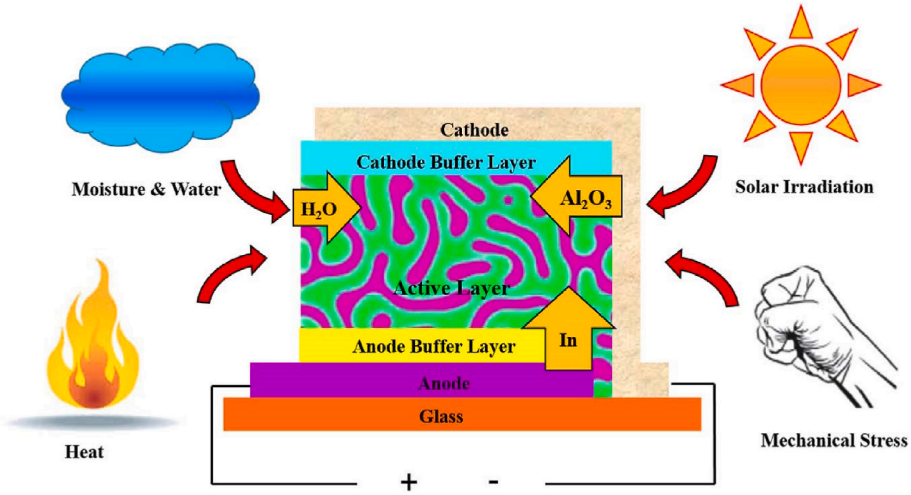


Fig. 8. Factors affecting device stability during degradation.

device and promote photooxidation of the bulk heterojunction layer [186]. The electrode and interfacial layers are also mobile, leading to significant device instability. The acidic and hygroscopic characteristics of the commonly used conductive polymers (PEDOT: PSS) photoactive layer induce the diffusion of indium and moisture into them, thereby shortening the lifespan of the device [185]. Furthermore, this diffusion leads to carrier entrapment and recombination, affecting energy levels of interfacial layers and shortening the device's lifetime.

4.1.1.1. Mechanical degradation. Mechanical deterioration is a less explored degradation process critical for the fabrication of OPVs and the operating stability of OPVs for portable and outdoor applications [23]. The flexibility properties of OPVs undergo significant bending and deformation. The polymer-fullerene layer, active layers, and interfaces are affected by mechanically induced degradation. Components exposed to atmospheric changes can suffer mechanical deterioration, such as delamination, cracks, scratches, punctures, and deformation, enabling degradation of all layers and contact points by water and oxygen [185].

4.1.2. *Extrinsic degradation*

OSC devices require consistent performance under light/dark, hot/cold, and dry/wet conditions [186]. The stability of OSC components in comparison to silicon-based solar cells is compromised. The OSCs exhibit 'burn-in' loss, an unexpected setback in efficiency upon initial operation [187]. The device's lifetime depends solely on a second phase, which exhibits a linear degradation trend. Extrinsic stability is guaranteed if the device is well sealed from the external environment since unsealed devices deteriorate quickly in the atmosphere, leading to poor performance within minutes [185].

4.1.2.1. Oxygen and water-based degradation. Organic material is vulnerable to exposure to water and oxygen, which can degrade the active layer of OPV devices. The OPV active layer is protected with encapsulation and other coatings [188]. However, water and oxygen may penetrate the active layer and affect the organic polymer, causing it to deteriorate [189]. Humidity in the bulk polymers induces an enhanced recombination pathway that reduces charge formation in the bulk heterojunction region. Yilmaz et al. [190] explored oxygen and water processing in OPV cells using isotope tagging and image-based mass spectrometry. Microscopic pinholes in the metal and aluminum electrodes allow oxygen and water molecules to enter the cells. The oxygen molecules affect the P3HT: PCBM cells under light exposure [191]. Therefore, limited access to oxygen and water is essential to prevent degradation and improve the OPV device stability.

4.1.2.2. Photo-degradation upon irradiation. The response of OPV is affected by several factors: environmental factors, light, and illumination. The absorption response of P3HT and P3HT: PCBM is dependent on the dark and illuminated environment, and the presence of P3HT and P3HT: PCBM is very stable when kept in an inert condition, but P3HT film degrades rapidly after 700 h of exposure to elevated temperatures and air [191,192]. In the presence of the PCBM, the bleaching of the polymer slowed down, resulting in a lower absorption loss. The photoconductivity of the blend declines more rapidly than that of pure P3HT films when exposed to air [193]. The formation of oxygen singlet states from oxygen triplets explains the photodegradation of π conjugated polymers such as P3HT and PCPDTBT in the presence of light and oxygen molecules. The decline of conjugated width in P3HT may act as a carrier extinguisher, reducing the emission strength after the degradation. P3HT blended with 10 % multi-walled by adding a buffer layer intermediate between the active layer and the electrode helps to counteract photo-instability [37].

4.2. *Stability of the solar cells*

The stability of organic PV devices improves the performance of polymer BHJ PV cells. Environmental and thermal stability are being evaluated, with thermal stability recording the highest impact. Prolonged exposures to increased temperatures increase the temperature of the photoactive materials, rendering solar cells unstable. Encapsulation can prevent oxygen and water from entering the device [189].

4.2.1. *Encapsulation materials*

Encapsulation is a crucial process in organic solar cell (OPV) cell encapsulation, which acts as an ultraviolet filter by removing harmful ultraviolet rays. This process increases mechanical stability and scratch resistance while minimizing the number of air and water radicals in the gadget cells [188]. Ultra-violet blocking coatings can enhance the long-term durability of OPV devices. Glass is a widely used encapsulation material but can crack under pressure. Polymers such as PET and PEN provide flexibility and low density, while metal films such as aluminium or copper offer strong resistance to water and oxygen [194]. Thin film coatings like SiO2 and TiO2 are also used but require specialized equipment [37]. The selection of encapsulating material is determined by the device's unique needs, like adaptability, simplicity, and protective qualities.

4.2.2. *Interfacial stability*

The interfacial layer of OPVs significantly impacts the device's efficiency and stability, serving as an essential functioning layer for charge transport and extraction. The interface layer preserves the active layer when the device storage short circuits, subsequently enhancing the environmental stability of the device by acting as a barrier layer to prevent water and oxygen entry.

Interface layers in organic semiconductor devices face problems such as acidity and hydrophilicity, leading to poor stability. Conventional ZnO becomes unstable under exposure to air and light, causing degradation of its active layer [190]. ZnO tackles stability difficulties in single ZnO-ETLs, with metal doping enhancing electron transport characteristics. To improve OPV efficiency and stability, other structures such as nanowires, nanorods, nanoflakes, and nanowalls are also employed as ETL material [185].

4.3. Manufacturing challenges

OPV devices typically involve solution processing, coating, printing, and thermal annealing to construct active and functional layers [195]. Ensuring that these diverse processing steps are compatible and optimizing the sequence of operations are essential for achieving high device performance [196]. A continuing challenge in the OPV field is developing manufacturing processes compatible with various materials and techniques [197]. Thin coating and printing technologies contribute essentially to organic solar cell development [198]. However, other processing techniques such as knife over the edge, slot die, and gravure coatings could dominate, even though it is difficult to anticipate which will be the most dominant in the future [19,199,200]. Despite these processes, the differences between experimental cell records and commercial OPV efficiencies are minimal compared to other commercial PV technologies. As a result, more effort is required in fabrication techniques to enable the large-scale deployment of OPV devices and to enable them to compete commercially with conventional inorganic solar cells. Addressing compatibility issues and optimizing fabrication processes for high-performance OPV devices requires a multidisciplinary approach involving collaboration among materials scientists, chemists, physicists, and engineers [201].

5. An alternative view on introducing composite materials in OPV technology

Introducing composite materials in organic photovoltaic (OPV) technology could revolutionize the field and overcome some imitations with purely organic or inorganic materials. Combining the unique properties of different materials, composite OPVs can enhance efficiency, stability, and flexibility, making them more viable for commercial applications [202,203]. Composite materials overcome the limitations of purely organic or inorganic materials.

i. Enhanced Efficiency:

Composite materials can combine the light-absorbing properties of organic molecules with the high charge mobility of inorganic materials. This combination can lead to improved photon harvesting and more efficient charge separation and transport within the device. For example, blending organic semiconductors with inorganic nanomaterials such as quantum dots or metal oxide nanoparticles can extend the absorption spectrum of the OPV, allowing for better utilization of the solar spectrum and higher overall efficiencies [204].

ii. Improved Stability:

One of the challenges with purely organic OPVs is their stability over time, especially when exposed to environmental factors such as moisture and oxygen [189]. By incorporating inorganic materials with excellent chemical and thermal stability, composite OPVs can exhibit enhanced resistance to degradation. Additionally, composite materials can mitigate material phase separation and morphological stability, which are common concerns in purely organic OPVs [205].

iii. Flexibility and Durability:

Purely organic OPVs are known for their flexibility, making them suitable for applications where traditional rigid silicon-based PVs are not feasible. However, pure organic materials may not always provide the mechanical and thermal robustness required for applications. Introducing composite materials promotes the production of flexible and durable OPVs that can withstand mechanical stress and temperature variations [206]. By combining the flexibility of organic materials with the mechanical strength of inorganic components, composite OPVs can offer a compelling solution for applications that demand flexibility and durability, such as wearable electronics and integration into building materials [207].

6. Future work

Earlier studies reported the optimization of OPV cells on a large scale. OPV has demonstrated effectiveness and promising technology to generate solar power efficiently. Polymer solar cells are thin, flexible, and semi-transparent, indicating their potential as a replacement for traditional cells. Critical efforts are underway to enhance the efficiency and stability and mitigate the deterioration of OPV cells for their widespread adoption.

Future work in organic photovoltaic technology revolves around addressing existing challenges of OPV efficiency, stability, and scalability through innovative research and technological advancements.

Future research should focus on new donor-acceptor materials with optimized energy levels, light absorption, and charge transport properties.

Implement optical management strategies by incorporating optical elements like light-trapping structures, plasmonic nanoparticles, or luminescent down-shifting layers to enhance light absorption and utilization within the active layer of OPV.

A stable material design approach is needed to improve the stability and degradation of OPV cells, involving selecting materials like active layer components and charge transport layers, developing encapsulation techniques, and ensuring long-term mechanical stability. Advanced characterization techniques and stable device configurations, such as inverted OPV structures, can contribute to overall stability. A combination of these methods can significantly enhance the performance of OPV cells.

Further study should explore the evolution of novel organic graphene materials and their derivatives. The properties of such novel materials should include high carrier mobility, excellent optical transparency, good mechanical flexibility, chemical stability, and compatibility with organic semiconductors.

7. Conclusion and recommendation

Earlier studies developed high-efficiency organic solar cells that operate at over 19 % under regulated circumstances. However, real-world replication of these outcomes and energy levels is still pending. Besides, silicon technology offers real-world efficiencies of 25 %, so the 19 % efficiency still lags. Classic silicon solar panels give an unrivaled return in most jurisdictions; we advise installing them if solar energy interests you.

In conclusion, the review has provided a comprehensive insight into the new technology of organic photovoltaic (OPV) performance, challenges, and potential applications. The study highlighted the significance of sustainable and accessible energy sources such as OPVs. The evolution of photovoltaic cell technology, spanning from traditional crystalline silicon to advanced OPVs, underscores the need for environmentally friendly and cost-effective alternatives. While silicon-based technologies have dominated the market, the emergence of OPVs, particularly with recent advancements in non-fullerene acceptors, signifies a promising shift towards more efficient and sustainable energy solutions. The review explores diverse applications of OPVs, ranging from building-integrated photovoltaic to portable electronics and automotive integration. The lightweight and flexibility of OPVs make them suitable for sustainable architecture and on-the-go power solutions, contributing to a greener and more energy-efficient future. Environmental benefits of OPVs, including low material toxicity, reduced carbon footprint, and the use of renewable resources in manufacturing, position them as environmentally friendly alternatives to traditional PV technologies. The market potential of OPVs is also highlighted, with projections indicating significant growth, driven by their low manufacturing costs and diverse applications. However, challenges such as degradation and stability issues, power conversion efficiency, and manufacturing complexities remain significant hurdles to be addressed urgently for widespread adoption. Strategies involving photoprotective mechanisms, stable material design, and multidisciplinary approaches are vital to tackling these problems and enhancing the performance of organic photovoltaic (OPV). Future work in OPV technology should focus on innovative research and technological advancements in novel photoactive materials development, interfacial engineering, device architectures, stability and lifetime improvement, roll-to-roll manufacturing, and hybrid and tandem technology. Addressing these key research areas through collaborative efforts among materials scientists, device engineers, and manufacturing experts can drive significant advancements in OPV technology, ultimately paving the way for its widespread adoption as a sustainable and cost-effective renewable energy solution.

CRediT authorship contribution statement

Charity M. Nkinyam: Conceptualization. **Chika Oliver Ujah:** Writing – original draft, Supervision, Formal analysis, Conceptualization. **Kingsley C. Nnakwo:** Writing – review & editing, Formal analysis. **Daramy V.V. Kallon:** Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] G. Adepoju, B. Adebanji, Feasibility study and optimal design of small hydropower-photovoltaic-diesel generator hybrid power system for itapaji-ekiti, Nigeria, J. Sci. Res. Rep. 11 (2) (2016) 1–10, https://doi.org/10.9734/jsrr/2016/26706.

[2] C.O. Ujah, D.V. Von Kallon, D.O. Aikhuele, Advanced composite materials: a panacea for improved electricity transmission, Appl. Sci. 12 (16) (2022), https://doi.org/10.3390/app12168291.

[3] S.O. Dahunsi, O.O. Fagbiele, E.O. Yusuf, Bioenergy technologies adoption in Africa: a review of past and current status, J. Clean. Prod. 264 (2020) 121683, https://doi.org/10.1016/j.jclepro.2020.121683.

[4] B. Adebanji, A. Ekiti, E.T. Fasina, A. Ekiti, S.A. Adeleye, A. Ekiti, Economic and Environmental Sustainability Assessment of Solar Photovoltaic Technology in Nigeria, Rural Electrification Perspective`, 2023.

[5] C.O. Ujah, A.P.I. Popoola, Review on materials applied in electric transmission conductors, J. Mater. Sci. 57 (3) (2022) 1581–1598, https://doi.org/10.1007/s10853-021-06681-9.

[6] N. Eustace, N. John, Economic evaluation of small-scale photovoltaic hybrid systems for mini-grid applications in far north Cameroon, Renew. Energy 35 (10) (2010) 2391–2398, https://doi.org/10.1016/j.renene.2010.03.005.

[7] E.M. Nfah, Evaluation of optimal photovoltaic hybrid systems for remote villages in Far North Cameroon, Renew. Energy 51 (2013) 482–488, https://doi.org/10.1016/j.renene.2012.09.035.

[8] H. Ajibade, C.O. Ujah, K.C. Nnakwo, D.V.V. Kallon, Improvement in battery technologies as panacea for renewable energy crisis, Discov. Appl. Sci. 6 (7) (2024), https://doi.org/10.1007/s42452-024-06021-x.

[9] B.A. Olanipekun, N.O. Adelakun, Assessment of renewable energy in Nigeria : challenges and benefits 68 (1) (2020) 64–67.

[10] and S.F.I. Osman, L. Chen, M. Yang, G. Msigwa, M. Farghali, Cost , environmental impact , and resilience of renewable energy under a changing climate, a Rev. Environ. Chem. Lett. 21 (2) (2023) 741–764, https://doi.org/10.1007/s10311-022-01532-8.

[11] Phebe Asantewaa Owusu, Phebe Asantewaa, A Review of Renewable Energy Sources, Sustainability Issues and Climate Change Mitigation, 2016.

[12] K. Ogueri, Renewable energy sources . Its benefits , potentials and challenges in Nigeria 5 (9) (2015) 21–25.

[13] A.O. Cyril, C.O. Ujah, B.N. Ekwueme, C.O. Asadu, Photovoltaic mini-grid incorporation: the panacea for electricity crisis in sub-Saharan Africa, Unconv. Resour. 4 (March) (2024) 100079, https://doi.org/10.1016/j.uncres.2024.100079.

[14] A. Jäger-waldau, Snapshot of Photovoltaics À May 2023, vol. 23, 2023, pp. 1–9.

[15] Y. Hua, M. Wei, J. Yuan, W. He, L. Chen, Y. Gao, The Impact of Climate Change on Solar Radiation and Photovoltaic Energy Yields in China, 2024.

[16] A. Elshurafa, Trends in Global Solar Photovoltaic Installation in 2023, 2024, pp. 2–5 [Online]. Available: https://www.kapsarc.org/research/publications/trends-in-global-solar-photovoltaic-installation-in-2023/.

[17] Dhabi. Abu, Global energy transformation: a roadmap to 2050, in: Int. Renew. Energy Agency, 2023.

[18] J.Y. Syed Azkar Ul Hasan, Muhammad Aleem Zahid, Sangheon Park, Stability Challenges for a Highly Efficient Perovskite/Silicon Tandem Solar Cell- A Review, Wiley Online Libr, 2024, https://doi.org/10.1002/solr.202300967 [Online]. Available:.

[19] I. Arbouch, Y. Karzazi, B. Hammouti, Organic photovoltaic cells: operating principles, recent developments and current challenges – review, Phys. Chem. News 72 (4) (2014) 73–84.

[20] li li, et al., From fullerene acceptors to non-fullerene acceptors: Prospects and challenges in the stability of organic solar cells, J. Mater. Chem. A 7 (41) (2019) 23361–23377.

[21] H. Fu, Z. Wang, Y. Sun, Advances in non-fullerene acceptor based ternary organic solar cells, Sol. RRL 2 (1) (2018), https://doi.org/10.1002/solr.201700158.

[22] J. Hou, O. Inganas, R.H. Friend, F. Gao, Organic solar cells based on non-fullerene acceptors, Nat. Mater. 17 (2) (2018) 119–128, https://doi.org/10.1038/NMAT5063.

[23] Y. Wang, et al., Recent progress and challenges toward highly stable nonfullerene acceptor-based organic solar cells, Adv. Energy Mater. 11 (5) (2021) 1–41, https://doi.org/10.1002/aenm.202003002.

[24] G.V. Bulavko, Organic photovoltaics: a journey through time, advancements, and future opportunities, Hist. Sci. Technol. 14 (1) (2024) 10–32, https://doi.org/10.32703/2415-7422-2024-14-1-10-32.

[25] J. Lv, et al., Phase separation and domain crystallinity control enable open-air-printable highly efficient and sustainable organic photovoltaics, InfoMat (2024) 1–13, https://doi.org/10.1002/inf2.12530. December 2023.

[26] G. Szabó, N.G. Park, F. De Angelis, P.V. Kamat, Are perovskite solar cells reaching the efficiency and voltage limits? ACS Energy Lett. 8 (9) (2023) 3829–3831, https://doi.org/10.1021/acsenergylett.3c01649.

[27] F.M. Zakai, S. Ijaz, N. Mahmood, M.Q. Mehmood, M.F. Khan, Smart Indoor Organic Photovoltaic Cells for Controlling Health Monitoring Sensors: Harnessing Sustainable Energy Solutions for Efficient Sensing Systems, vol. 12999, 2024, p. 109, https://doi.org/10.1117/12.3022086.

[28] M.A. Almeida, Recent advances in solar cells. Solar Cells, first ed., Springer, Switzerland, 2020, pp. 79–122, https://doi.org/10.1007/978-3-030-36354-3_4.

[29] E.K. Solak, E. Irmak, Advances in organic photovoltaic cells: a comprehensive review of materials, technologies, and performance, RSC Adv. 13 (18) (2023) 12244–12269, https://doi.org/10.1039/d3ra01454a.

[30] M.M.K.S. Dan Zhang, Han-Hee Cho, Jun-Ho Yum, An organic semiconductor photoelectrochemical tandem cell for solar water splitting, Adv. Energy Mater. 12 (42) (2022), 2202363-2202363.

[31] L.M. Riede, D. Spoltore, Organic Solar Cells — the Path to Commercial Success, 2021, pp. 1–10, https://doi.org/10.1002/aenm.202002653.

[32] Y. Andreas Weu, Rhea Kumar, Julian F. Butscher, Julian F. Butscher, Lami Vincent, Lami Vincent, Fabian Paulus, Fabian Paulus, Artem A. Bakulin, Energy Transfer to a Stable Donor Suppresses Degradation in Organic Solar Cells, 2019.

[33] J.M. Herz, Effect of ultraviolet radiation on organic photovoltaic materials and devices, ACS Appl. Mater. Interfaces 11 (Issue 24) (2019) 21543–21551, https://doi.org/10.1021/acsami.9b04828 [Online]. Available:.

[34] A.P. Yadav, Kumar, Enhancement in efficiency of PV cell through P&O algorithm, Int. J. Technol. Res. Eng. 2 (2015) 2642–2644.

[35] P.K.S. Barada, P. Dash a, Swaraj Kumar Beriha, Brundabana Naik, Organic Materials Based Solar Cells, vol. 67, 2022, pp. 1057–1063.

[36] Y. Srinivas, B. Balaji, S. Nagendra Babu, Review on present and advance materials for solar cells, Int. J. Eng. Res. Online 3 (2015) 178–182.

[37] S.K. Gupta, K. Dharmalingam, L.S. Pali, S. Rastogi, A. Singh, A. Garg, Degradation of organic photovoltaic devices: a review, Nanomater. Energy 2 (1) (2013) 42–58, https://doi.org/10.1680/nme.12.00027.

[38] M. I, F.I. Muhammad Aamir Iqbal, Maria Malik, Wajeehah Shahid, Syed Zaheer Ud Din, Nadia Anwar, Materials for Photovoltaics: Overview, Generations, Recent Advancements and Future Prospects, 2022, https://doi.org/10.5772/intechopen.101449.

[39] J. P, P. Węgierek, Photovoltaic Cell Generations and Current Research Directions for Their Development, vol. 15, 2022, https://doi.org/10.3390/ma15165542, 16.

[40] R.T.A. Ezhov, E. Alexey, K. Zhdanova, P. Zhdanov, N. Klyukin, Y. Zhizhin, N. Bragina, F. Mironov, Synthesis of Zn(II) porphyrin dyes and revealing an

influence of their alkyl substituents on performance of dye-sensitized solar, Cells (2020) 269.

[41] O. S, S.H.Z.N. Asim, K. Sopian, S. Ahmadi, K. Saeedfar, M.A. Alghoul, A review on the role of materials science in solar cells, Renew. Sustain. Energy Rev. 16 (2012) 5834–5847.

[42] Ibn-Mohammed, Perovskite Solar Cells: an Integrated Hybrid Lifecycle Assessment and Review in Comparison with Other Photovoltaic Technologies Elsevier, 2017, pp. 1321–1344.

[43] K. Nikolaidou, S. Sarang, S. Ghosh, Solar Photovoltaic Technology : A Review of Different Types of Solar Cells and its Future Trends Solar Photovoltaic Technology : A Review of Different Types of Solar Cells and its Future Trends, 2021, https://doi.org/10.1088/1742-6596/1913/1/012053.

[44] Y. Lee, B. Kim, S.M. Ifitiquar, Silicon Solar Cells : Past , Present and the Future Silicon Solar Cells : Past , Present and the Future, 2014, https://doi.org/10.3938/jkps.65.355. May 2016.

[45] G.M. Sampaio PG, Photovoltaic solar energy: conceptual framework, Renew. Sustain. Energy Rev. 74 (2017) 590–601.

[46] T. Saga, Advances in crystalline silicon solar cell technology for industrial mass production, NPG Asia Mater. 2 (3) (2010) 96–102, https://doi.org/10.1038/asiamat.2010.82.

[47] Monocrystalline silicon,” https://en.wikipedia.org/wiki/Monocrystalline_silicon.

[48] Manufacturing Polycrystalline Silicon, 2019. https://solaron.net/solar/manufacturing-polycrystalline-silicon/.

[49] K.L.V. Chopra, P.D. Paulson, Dutt, Thin-film solar cells: an overview, Prog. Photovoltaics 12 (2004) 69–92.

[50] S.S. Jayawardena KI, L.J. Rozanski, C.A. Mills, M.J. Beliatis, N.A. Nismy, Inorganics-in-Organics’: recent developments and outlook for 4G polymer solar cells, Nanoscale 5 (18) (2013) 8411–8427.

[51] S. Sivaraj, R. Rathansamy, G.V. Kaliyannan, H. Panchal, A Comprehensive Review on Current Performance , Challenges and Progress in Thin-Film Solar Cells, 2022, pp. 1–33.

[52] Amorphous silicon,” https://en.wikipedia.org/wiki/Amorphous_silicon.

[53] P. Paulson, M. Technology, V. Dutta, Thin-Film Solar Cells: an Overview, 2017, https://doi.org/10.1002/pip.541. March 2004.

[54] M.A. Maehlum, Energy informative the homeowner’s guide to solar panels, best thin film solar panels—amorphous, in: Cadmium Telluride or CIGS?, 2015.

[55] D.B. Li, et al., 20%-efficient polycrystalline Cd(Se,Te) thin-film solar cells with compositional gradient near the front junction, Nat. Commun. 13 (1) (2022) 1–8, https://doi.org/10.1038/s41467-022-35442-8.

[56] R.A. Mcintyre, State of the Art of Photovoltaic Technologies, vol. 93, 2010, pp. 361–392, https://doi.org/10.3184/003685010X12871589883476.

[57] A.A. Laurence Stamford, Environmental Impacts of Copper-Indium-Gallium-Selenide (CIGS) Photovoltaics and the Elimination of Cadmium through Atomic Layer Deposition, vol. 688, 2019, pp. 1092–1101, https://doi.org/10.1016/j.scitotenv.2019.06.343.

[58] A.H. Grandidier J, D.M. Callahan, J.N. Munday, Gallium arsenide solar cell absorption enhancement using whispering gallery modes of dielectric nanospheres, IEEE J. Photovoltaics 2 (2) (2012) 123–128.

[59] F. Dimroth, J.F. Geisz, N.J. Ekins-daukes, Multi-junction Solar Cells Paving the Way for Super High-Efficiency, 2021, https://doi.org/10.1063/5.0048653.

[60] J.C. Boisvert, X. Zhang, D.E. Joslin, N.H. Karam, Multijunction Solar Cell Development and Production at Spectrolab, 2019, pp. 153–159.

[61] B. Gong, Research Progress of Potential Solar Cells Alternative, vol. 83, 2024, pp. 655–661.

[62] D. Wei, Dye Sensitized Solar Cells, June, 2014, https://doi.org/10.3390/ijms11031103.

[63] K. Sharma, V. Sharma, S.S. Sharma, Dye-Sensitized Solar Cells : Fundamentals and Current Status, vol. 6, 2018.

[64] P.D. Sekaran, R. Marimuthu, An extensive analysis of dye-sensitized solar cell (DSSC), Braz. J. Phys. 54 (1) (2024), https://doi.org/10.1007/s13538-023-01375-w.

[65] N. Park, Perovskite solar cells : an emerging photovoltaic technology, Biochem. Pharmacol. (August 2014, 2015), https://doi.org/10.1016/j.mattod.2014.07.007.

[66] F. Saleh, Z.A.M. Hazaea, A. Ghaleb, F. Murshed, Perovskite solar cells (PSCs): definition , structure , and, Sol. Cells Dev. (April, 2023), https://doi.org/10.5281/zenodo.7765612.

[67] O. Access, The King of the New Generation Photovoltaic Technologies —— Perovskite Solar Cells & the Opportunities and Challenges the King of the New Generation Photovoltaic Technologies — — Perovskite Solar Cells & the Opportunities and Challenges, 2020, https://doi.org/10.1088/1757-899X/926/1/012010.

[68] S. Samukawa, Quantum dot superlattice structure for high efficiency solar cells utilizing a bio-template and damage-free neutral beam etching. 2012 IEEE 11th International Conference on Solid-State and Integrated Circuit Technology, Xi’an, China, 2012, pp. 1–4, https://doi.org/10.1109/ICSICT.2012.6467698.

[69] O.E. Semonin, J.M. Luther, M.C. Beard, Quantum dots for next- generation photovoltaics, Mater. Today 15 (11) (2012) 508–515, https://doi.org/10.1016/S1369-7021(12)70220-1.

[70] A.F. Freitas, J.N. Gonçalves, A.S. Nogueira, A comprehensive review of the application of chalcogenide nano particles in polymer solar cells, Nanoscale 6 (2014) 6371–6397.

[71] C. Bates, “Everything You Need to Know about Organic Solar Cells.”.

[72] M.A. Green, et al., Solar cell efficiency tables (Version 63), Prog. Photovoltaics Res. Appl. 32 (1) (2024) 3–13, https://doi.org/10.1002/pip.3750.

[73] V. Sharma, S.S. Chandel, Performance and degradation analysis for long term reliability of solar photovoltaic systems: a review, Renew. Sustain. Energy Rev. 27 (2013) 753–767, https://doi.org/10.1016/j.rser.2013.07.046 [Online]. Available:.

[74] N. Shah, et al., A review of third generation solar cells, Processes 11 (6) (2023), https://doi.org/10.3390/pr11061852.

[75] K. Yoshikawa, et al., Silicon heterojunction solar cell with interdigitated back contacts for a photoconversion efficiency over 26%, Nat. Energy 2 (5) (2017) https://doi.org/10.1038/nenergy.2017.32.

[76] K.M. Hitoshi Sai, Takuya Matsui, Thin-film microcrystalline silicon solar cells: 11.9% efficiency and beyond, Appl. Phys. Express 11 (iss 2) (2018), https://doi.org/10.7567/APEX.11.022301.

[77] A.S. Atib Mohammad Oni, M.M. Rahman, M.B.H. Bhuian, A comprehensive evaluation of solar cell technologies, associated loss mechanisms, and efficiency enhancement strategies for photovoltaic cells, Energy Rep. 11 (2024) 3345–3366, https://doi.org/10.1016/j.egyr.2024.03.007 [Online]. Available:.

[78] Q. Liu, K. Vandewal, Understanding and suppressing non-radiative recombination losses in non-fullerene organic solar cells, Adv. Mater. 35 (35) (2023), https://doi.org/10.1002/adma.202302452.

[79] L. Zhu et al., “Supplementary Information for Single-junction organic solar cells with over 19 % efficiency enabled by a refined double-fibril network morphology Frontiers Science Center for Transformative Molecules , In-situ Center for Physical Science , School of Mater”.

[80] W. Chen, et al., Monolithic perovskite/organic tandem solar cells with 23.6% efficiency enabled by reduced voltage losses and optimized interconnecting layer, Nat. Energy v. 7 (2022) 229–237. March.

[81] M.S.A. Kamel, A. Al-jumaili, Inorganic nanoparticles to overcome efficiency inhibitors of organic photovoltaics: an in-depth review, Renewable Sustainable Energy Rev. (2022) 166, https://doi.org/10.1016/j.rser.2022.112661.

[82] N. Lal, et al., Optics and light trapping for tandem solar cells on silicon, IEEE J. Photovoltaics 4 (6) (2014) 1380–1386, https://doi.org/10.1109/JPHOTOV.2014.2342491.

[83] K. T, A.K.H. Haloui, Modeling of a hybrid thermal photovoltaic (PVT) collector based on thin film organic solar cells, Elec. Power Syst. Res. 210 (2022) 108–131, https://doi.org/10.1016/j.epsr.2022.108131.

[84] T. Review, The Future of Organic Photovoltaics, 2014, https://doi.org/10.1039/x0xx00000x.

[85] M.D. Chatzisideris, A. Laurent, M.Z. Hauschild, Environmental impacts of electricity self-consumption from organic photovoltaic battery systems at industrial facilities in Denmark, CIRP Ann. Manuf. Technol. 66 (2017) 45–48.

[86] F.C.K. Gisele Alves dos Reis Benatto, Nieves Espinosa Martinez, Life-Cycle Assessment of Solar Charger with Integrated Organic Photovoltaics, 2017.

[87] D.V. Cutting, C.L. Cutting, M. Bag, D. Venkataraman, J. Mater. Chem. C (4) (2016) 10367–10370. J. Mater. Chem. C.

[88] H.P. Yu, Gradient Al-doped ZnO multi-buffer layers: effect on thephotovoltaic properties of organic solar cells, Mater. Lett. 161 (2015) 624–627.

[89] A. Jannat, M.F. Rahman, M.S. Hossain, A review study of organic photovoltaic cell 4 (1) (2013) 1–6.

[90] L. Duan, A. Uddin, Progress in Stability of Organic Solar Cells, Adv. Sci 7 (2020) 1903259. https://doi.org/10.1002/advs.201903259.

[91] C. Status, Account/Review for Frontiers of Molecular Science Sma Ll Mo L Ecu L Es F or Vacuum-Processed Organ I C Photovo L Ta I Cs, 2021, https://doi.org/10.1246/bcsj.20200330.

[92] P.B. Yong Cui, Huifeng Yao, Ling Hong, Tao Zhang, Yabing Tang, Baojun Lin, Kaihu Xian, Bowei Gao, Cunbin An, Organic photovoltaic cell with 17% efficiency and superior processability, Natl. Sci. Rev. 7 (7) (2020) 1239–1246, https://doi.org/10.1093/nsr/nwz200 [Online]. Available:.

[93] A.K.P. Ajay Jain, Richa Kothari, V.V. Tyagi, Reji Kumar Rajamony, Muhammad Shakeel Ahmad, Har Mohan Singh, Shubham Raina, Advances in organic solar cells: materials, progress, challenges and amelioration for sustainable future Author links open overlay panel, Sustain. Energy Technol. Assessments 63 (2024) 103632. https://doi.org/10.1016/j.seta.2024.103632.

[94] X. Wang, et al., Recent progress of organic photovoltaics with efficiency over 17%, Energies 14 (14) (2021) https://doi.org/10.3390/en14144200.

[95] M.D. Tyona, A theoritical study on spin coating technique 2 (4) (2013) 195–208.

[96] A.C. Mendhe, Spin Coating: Easy Technique for Thin Films, 2023, pp. 387–424 [Online]. Available: https://link.springer.com/chapter/10.1007/978-981-99-0961-2_9.

[97] R. Ramos-hern, P. Enrique, F.D. Calvo, M.F. Beristain, M. Cer, M.J. Percino, Solvent Effect on Small-Molecule Thin Film Formation Deposited Using the Doctor Blade Technique, 2023, pp. 1–8.

[98] online source at, National renewable energy laboratory, best research-cell efficiency charts [Online]. Available: https://www.nrel.gov/pv/cell-efficiency.html, 2023. (Accessed 25 February 2024).

[99] C.R.Y. Huang, E.J. Kramer, A.J. Heeger, G.C. Bazan, Y. Huang, E. J. Kramer, A. J. Heeger, G. C. Bazan, Chem. Rev. 114 (2014) 7006.

[100] C. Li, et al., Achieving record-efficiency organic solar cells upon tuning the conformation of solid additives, J. Am. Chem. Soc. 144 (32) (2022) 14731–14739, https://doi.org/10.1021/jacs.2c05303.

[101] F. Shi, et al., A nitroxide radical conjugated polymer as an additive to reduce nonradiative energy loss in organic solar, Cells 2212084 (2023), https://doi.org/10.1002/adma.202212084.

[102] Y. Cui, et al., Organic photovoltaic cell with 17% efficiency and superior processability, Natl. Sci. Rev. 7 (7) (2021) 1239–1246, https://doi.org/10.1093/NSR/NWZ200.

[103] J.H. Yong Cui, Ye Xu, Huifeng Yao, Pengqing Bi, Ling Hong, Jianqi Zhang, Yunfei Zu, Tao Zhang, JiYong Cui, Ye Xu, Huifeng Yao, Pengqing Bi, Ling Hong, Jianqi Zhang, Yunfei Zu, Tao Zhang, Jinzhao Qin, Junzhen Ren, Zhihao Chen, Chang He, Hao Xiaotao, Zhixiang We, Single-junction organic photovoltaic cell with 19% efficiency, Adv. Mater. 33 (41) (2021), https://doi.org/10.1002/adma.202102420 [Online]. Available:.

[104] X. Si, et al., Achieving organic solar cells with an efficiency of 18.80% by reducing nonradiative energy loss and tuning active layer morphology, Adv. Funct. Mater. 33 (47) (2023), https://doi.org/10.1002/adfm.202306471.

[105] J. Karzazi, I. Arbouch, Environ. Sci. 5 (2014) 1505.

[106] L. Lu, M.A. Kelly, W. You, L. Yu, Status and prospects for ternary organic photovoltaics, Nat. Publ. Gr. 9 (8) (2015) 491–500, https://doi.org/10.1038/nphoton.2015.128.

[107] M.H. Seiichiro Izawa, Armand Perrot, Ji-Hyun Lee, Organic Pn Homojunction Solar Cell, vol. 71, 2019, pp. 45–49.

[108] Y. Li, X. Huang, H.K.M. Sheriff, S.R. Forrest, Semitransparent organic photovoltaics for building-integrated photovoltaic applications, Nat. Rev. Mater. 8 (3) (2023) 186–201, https://doi.org/10.1038/s41578-022-00514-0.

[109] A. Wagenpfahl, Mobility dependent recombination models for organic solar cells, J. Phys. Condens. Matter 29 (2017), https://doi.org/10.1088/1361-648X/aa7952.

[110] K. Phlipps, Investigation in Linker Functionality of Main-Chain Thermally Activated Delayed Fluorescence Polymers and Through-Space Charge Transfer in Supramolecular Polymers, 2021.

[111] Toggle the table of contents Organic solar cell," https://en.wikipedia.org/wiki/Organic_solar_cell.

[112] K.A. Vivek, G.D. Agrawal, Organic Solar Cells : Principles , Mechanism and Recent Dvelopments, 2014, pp. 2319–2322.

[113] R.C. Chiechi, R.W.A. Havenith, J.C. Hummelen, L.J.A. Koster, Modern plastic solar cells: materials, mechanisms and modeling, Mater. Today 16 (2013) 281–289.

[114] S.B. Singh, D. Chauhan, A. Iqbal, Study of organic solar cell, ICONIC Res. Eng. J. 1 (10) (2018) 29–32.

[115] S.B. Darling, Charge generation in organic photovoltaics: a review of theory and computation, Mol. Syst. Des. Eng. 1 (10) (2016), https://doi.org/10.1039/c6me00005c.

[116] C. Deibe, T. Strobe, V. Dyakonov, Role of the charge transfer state in organic donor-acceptor solar cells, Adv. Mater. 22 (37) (2010) 4097–4111, https://doi.org/10.1002/adma.201000376.

[117] M. Hermle, et al., Passivating contacts and tandem concepts: approaches for the highest silicon-based solar cell efficiencies, Appl. Phys. Rev. (7) (2020), https://doi.org/10.1063/1.5139202 [Online]. Available:.

[118] A. Sharma, S. Masoumi, D. Gedefaw, S. O'Shaughnessy, D. Baran, A. Pakdel, Flexible solar and thermal energy conversion devices: organic photovoltaics (OPVs), organic thermoelectric generators (OTEGs) and hybrid PV-TEG systems, Appl. Mater. Today 29 (2022) 101614. https://doi.org/10.1016/j.apmt.2022.101614.

[119] B.S. Yan-GYan-Gang Bi, Jing Feng EMAIL logo, Jin-Hai Ji, Fang-Shun Yi, Yun-Fei Li, Yue-Feng Liu, Xu-Lin Zhang, Hong-Bo Sunang Bi, Jing Feng EMAIL logo, Jin-Hai Ji, Fang-Shun Yi, Yun-Fei Li, Yue-Feng Liu, Nanostructures induced light harvesting enhancement in organic photovoltaics, Nanophotonics (2017), https://doi.org/10.1515/nanoph-2017-0060 [Online]. Available:.

[120] R.B.W. Gerhard Seifert, Isolde Schwedler, Jens Schneider, Light management in solar modules, in: Photon Management in Solar Cells, 2015, https://doi.org/10.1002/9783527665662.ch12 [Online]. Available:.

[121] H. Liu, Y. Du, X. Yin, M. Bai, W. Liu, Micro/nanostructures for light trapping in monocrystalline silicon solar cells, J. Nanomater. 2022 (2022), https://doi.org/10.1155/2022/8139174.

[122] A.I. Hofmann, E. Cloutet, G. Hadziioannou, Materials for transparent electrodes: from metal oxides to organic alternatives, Adv. Electron. Mater. 4 (10) (2018), https://doi.org/10.1002/aelm.201700412.

[123] C.F. L, I.C.C.Y.S. Li, C.H. Tsai, S.H. Kao, I.W. Wu, J.Z. Chen, C.I. Wu, Single-layer organic–inorganic-hybrid thin-film encapsulation for organic solar cells, J. Phys. D Appl. Phys. (46) (2013) 435–502, https://doi.org/10.1088/0022-3727/46/43/435502.

[124] C. Of, O. Solar, Ogechi Vivian Nwadiaru Master in Energy , Engineering Track President : Prof . Youm Issakha Supervisor : Dr . Harald Hoppe External Examiner : Dr . Sofiane Amara Internal Examiner, Dr . Abdellah Benyoucef, 2017, pp. 2016–2017.

[125] C.Y. Liao, et al., Processing strategies for an organic photovoltaic module with over 10% efficiency, Joule 4 (1) (2020) 189–206, https://doi.org/10.1016/j.joule.2019.11.006.

[126] M. T., H.I.J. Lee, T. Sagawa, Modeling of optimum size and shape for high photovoltaic performance of poly(3-hexylthiophene) nanopore in interdigitated bilayer organic solar cells, Org. Electron. (28) (2016) 59–66, https://doi.org/10.1016/j.orgel.2015.09.026.

[127] T.C. Mutlu A, M. Can, Performance improvement of organic solar cell via incorporation of donor type self-assembled interfacial monolayer, Thin Solid Films 685 (2019) 88–96, https://doi.org/10.1016/j.tsf.2019.05.064.

[128] T. Paula, M.D.F. Marques, Recent advances in polymer structures for organic solar cells: a review, AIMS Energy 10 (1) (2022) 149–176, https://doi.org/10.3934/ENERGY.2022009.

[129] D. Zhang, B. Fan, N. Li, C.J. Brabec, Recent Progress in Thick-Film Organic Photovoltaic Devices : Materials , Devices , and Processing, 2021, pp. 4–23, https://doi.org/10.1002/sus2.10. January.

[130] L.T. Ng, S.W. Lee, D.W. Chang, J.M. Hodgkiss, D. Vak, Organic photovoltaics ' new renaissance : advances toward roll-to-roll manufacturing of non-fullerene acceptor organic photovoltaics 2101556 (2022), https://doi.org/10.1002/admt.202101556.

[131] P. Wang, Y. Zhao, T. Wang, Recent Progress and Prospects of Integrated Perovskite/Organic Solar Cells, July, 2020, https://doi.org/10.1063/5.0013912.

[132] H. C, H.K.Y. Lee, S. Biswas, Record high efficiency achievement under LED light in low bandgap donor-based organic solar cell through optimal design, Int. J. Energy Res. (2023), https://doi.org/10.1155/2023/3823460.

[133] Y. Xie, Q. Xue, Q. Yao, S. Xie, T. Niu, H. Yip, Monolithic perovskite/organic tandem solar cells: developments, prospects, and challenges, Nano Sel 2 (7) (2021) 1266–1276, https://doi.org/10.1002/nano.202000287.

[134] P. Cheng, Y. Yang, Narrowing the Band Gap : the Key to High-Performance Organic Photovoltaics Narrowing the Band Gap : the Key to High-Performance Organic Photovoltaics, May, 2021, https://doi.org/10.1021/acs.accounts.0c00157.

[135] F.-C. Chen, "Organic Semiconductors," Encyclopedia of Modern Optics (second ed.),.

[136] Department of Energy," https://www.energy.gov/eere/solar/organic-photovoltaics-research.

[137] F.C. Krebs, Fabrication and processing of polymer solar cells: a review of printing and coating techniques 93 (Issue 4) (2009) 394–412.

[138] T. Paula, M.D.F. Marques, Recent advances in polymer structures for organic solar cells : a review 10 (March) (2022) 149–176, https://doi.org/10.3934/energy.2022009.

[139] S.B. Darling, F. You, RSC Adv. (2015) 17633–17648, https://doi.org/10.1039/c3ra42989j.

[140] M.S.A. Kamel, M. Oelgemöller, M.V. Jacob, Sustainable plasma polymer encapsulation materials for organic solar cells, Journal of Materials Chemistry A 10 (9) (2022) 4683–4694. https://doi.org/10.1039/d1ta10608b.

[141] M.L. Yannick-Serge Zimmermann, Andreas Schäffer, Christoph Hugi, Karl Fent, Philippe F-X Corvini, Organic Photovoltaics: Potential Fate and Effects in the Environment, 2012, https://doi.org/10.1016/j.envint.2012.08.015.

[142] C.A. Wolden, et al., Photovoltaic manufacturing: present status, future prospects, and research needs, J. Vac. Sci. Technol. A Vacuum, Surfaces, Film. 29 (3) (2011), https://doi.org/10.1116/1.3569757.

[143] E.I. Ebru Kondolot Solaka, Advances in organic photovoltaic cells: a comprehensive review of materials, technologies, and performance 13 (18) (2023) 12244–12269, https://doi.org/10.1039/d3ra01454a.

[144] C.J. Brabec, Organic photovoltaics: technology and market, Sol. Energy Mater. Sol. Cells 83 (2–3) (2004) 273–292, https://doi.org/10.1016/j.solmat.2004.02.030.

[145] D.K. Joonam Park, Kyung Taek Bae, et al., Unraveling the limitations of solid oxide electrolytes for all-solid-state electrodes through 3D digital twin structural analysis, Nano Energy 79 (2021), https://doi.org/10.1016/j.nanoen.2020.105456 [Online]. Available:.

[146] J. Wang, H. Zhang, Material innovations and scalable manufacturing for next-generation advanced organic photovoltaics, Highlights Sci. Eng. Technol. 96 (2024) 245–250, https://doi.org/10.54097/h1pn6d69.

[147] I. Burgués-Ceballos, et al., Transparent organic photovoltaics: a strategic niche to advance commercialization, Joule 5 (9) (2021) 2261–2272, https://doi.org/10.1016/j.joule.2021.07.004.

[148] S. Lizin, et al., Life cycle analyses of organic photovoltaics: a review, Energy Environ. Sci. 6 (11) (2013) 3136–3149, https://doi.org/10.1039/c3ee42653j.

[149] E. Buitrago, A.M. Novello, T. Meyer, Third-generation solar cells: toxicity and risk of exposure, Helv. Chim. Acta 103 (9) (2020), https://doi.org/10.1002/hlca.202000074.

[150] N. Espinosa, M. Hösel, D. Angmo, F.C. Krebs, Solar cells with one-day energy payback for the factories of the future, Energy Environ. Sci. 5 (1) (2012) 5117–5132, https://doi.org/10.1039/c1ee02728j.

[151] K. A. M., C.K. Luscombe, The future of organic photovoltaics journal, Chem. Soc. Rev. 44 (1) (2015) 78–90, https://doi.org/10.1039/x0xx00000x.

[152] B. Azzopardi, C.J.M. Emmott, A. Urbina, F.C. Krebs, J. Mutale, J. Nelson, Economic assessment of solar electricity production from organic-based photovoltaic modules in a domestic environment, Energy Environ. Sci. 4 (10) (2011) 3741–3753, https://doi.org/10.1039/c1ee01766g.

[153] J.H. Jianqiu Wang, Zhong Zheng, Yunfei Zu, Yafei Wang, Xiaoyu Liu, Shaoqing Zhang, Maojie Zhang, A tandem organic photovoltaic cell with 19.6% efficiency enabled by light distribution control, Adv. Mater. (2021), https://doi.org/10.1002/adma.202102787 [Online]. Available:.

[154] Y. He, et al., Industrial viability of single-component organic solar cells, Joule 6 (6) (2022) 1160–1171, https://doi.org/10.1016/j.joule.2022.05.008.

[155] A.C. Lazaroiu, M. Gmal Osman, C.V. Strejoiu, G. Lazaroiu, A comprehensive overview of photovoltaic technologies and their efficiency for climate neutrality, Sustain. Times 15 (23) (2023), https://doi.org/10.3390/su152316297.

[156] A. Andersson, Electrical performance study of organic photovoltaics for indoor applications: with potential in Internet of Things devices [Online]. Available: https://www.diva-portal.org/smash/record.jsf?pid=diva2:1438809, 2020.

[157] S.M. Wang, P. Baek, A. Akbarinejad, Conjugated polymers and composites for stretchable organic electronics, J. Mater. Chem. C 7 (5534–5552) (2019).

[158] P. Singh, N.M. Ravindra, Temperature dependence of solar cell performance - an analysis, Sol. Energy Mater. Sol. Cells 101 (2012) 36–45, https://doi.org/10.1016/j.solmat.2012.02.019.

[159] M.N. Zidan, N. Everitt, T. Ismail, I.S. Fahim, Review organic solar cells parameters extraction and characterization techniques, Polymers 13 (19) (2021) 1–19, https://doi.org/10.3390/polym13193224.

[160] B. Xiao, P. Calado, R.C.I. MacKenzie, T. Kirchartz, J. Yan, J. Nelson, Relationship between fill factor and light intensity in solar cells based on organic disordered semiconductors: the role of tail states, Phys. Rev. Appl. 14 (2) (2020) 1–17, https://doi.org/10.1103/PhysRevApplied.14.024034.

[161] M.H. Jao, H.C. Liao, W.F. Su, Achieving a high fill factor for organic solar cells, J. Mater. Chem. A 4 (16) (2016) 5784–5801, https://doi.org/10.1039/c6ta00126b.

[162] T. Ameri, N. Li, C.J. Brabec, Highly efficient organic tandem solar cells: a follow up review, Energy Environ. Sci. 6 (8) (2013) 2390–2413, https://doi.org/10.1039/c3ee40388b.

[163] A.H.I. Mohamed, M.L.I. Ibrahim, Influence of light absorption profile on the performance of organic photovoltaics, IIUM Eng. J. 22 (2) (2021) 135–148, https://doi.org/10.31436/iiumej.v22i2.1559.

[164] I.M. Horta, A.G. Jr, B.S. Damasceno, A.L. de J. Pereira, D.M.G. Leite, A.S. da S. Sobrinho, 10 - development of metal oxide heterostructures for photovoltaic and solar cell applications, Met. Oxide-Based Heterostruct (2023) 359–389, https://doi.org/10.1016/B978-0-323-85241-8.00001-3 [Online]. Available:.

[165] C.J. Brabec, et al., Material strategies to accelerate OPV technology toward a GW technology, Adv. Energy Mater. 10 (43) (2020) 1–10, https://doi.org/10.1002/aenm.202001864.

[166] P. Li, Energy Level Alignment at Donor-Acceptor Interfaces and its Correlation with Open-Circuit Voltage, 2017.

[167] A. Uddin, M.A. Green, Donor-acceptor interface and conversion efficiency, Mater. Sci. Res. J. 7 (2) (2013) 229–254.

[168] M.W. Hua Zhang, Xianfeng Qiao, Yan Shen, Effect of temperature on the efficiency of organometallic perovskite solar cells, J. Energy Chem. 24 (6) (2015) 729–735, https://doi.org/10.1016/j.jechem.2015.10.007 [Online]. Available:.

[169] A.M. Elbreki, A.F. Muftah, K. Sopian, H. Jarimi, A. Fazlizan, A. Ibrahim, Experimental and economic analysis of passive cooling PV module using fins and planar reflector, Case Stud. Therm. Eng. 23 (2021) 100801, https://doi.org/10.1016/j.csite.2020.100801. December 2020.

[170] D. Colarossi, P. Principi, Indoor and outdoor performance of an enhanced photovoltaic panel through graphene/fins/phase change materials, Appl. Sci. 11 (19) (2021), https://doi.org/10.3390/app11198807.

[171] E. Sen, M.S. Celiktas, Performance evaluation and thermal stabilization of photovoltaic panels using phase-change materials, Energy 302 (2024), https://doi.org/10.1016/j.energy.2024.131840 [Online]. Available:.

[172] H.M. Metwally, Investigation of PV Cooling Process Using Hybrid System, January, 2022, https://doi.org/10.13140/RG.2.2.34293.65761.

[173] K. Hasan, S.B. Yousuf, M.S.H.K. Tushar, B.K. Das, P. Das, M.S. Islam, Effects of different environmental and operational factors on the PV performance: a comprehensive review, Energy Sci. Eng. 10 (2) (2022) 656–675, https://doi.org/10.1002/ese3.1043.

[174] Y. Li, W. Huang, D. Zhao, L. Wang, Z. Jiao, Q. Huang, P. Wang, Recent progress in organic solar cells: a review on materials from acceptor to donor, Molecules 27 (6) (2022) 1800, https://doi.org/10.3390/molecules27061800.

[175] J. Yao, et al., Cathode engineering with perylene-diimide interlayer enabling over 17% efficiency single-junction organic solar cells, Nat. Commun. 11 (1) (2020) 1–10, https://doi.org/10.1038/s41467-020-16509-w.

[176] Y. Cui, et al., Single-junction organic photovoltaic cells with approaching 18% efficiency, Adv. Mater. 32 (19) (May 2020), https://doi.org/10.1002/adma.201908205.

[177] B. Mohamed, et al., Latest Updates of Single-Junction Organic Solar Cells up to 20% Efficiency, 2023, pp. 1–12.

[178] S. Rasool, et al., Path to the fabrication of efficient, stable and commercially viable large-area organic solar cells, Mater. Futur. 2 (3) (2023), https://doi.org/10.1088/2752-5724/acd6ab.

[179] Y. Chang, et al., Achieving efficient ternary organic solar cells using structurally similar non-fullerene acceptors with varying flanking side chains, Adv. Energy Mater. 11 (14) (2021), https://doi.org/10.1002/aenm.202100079.

[180] Z. Zheng, et al., Tandem organic solar cell with 20.2% efficiency, Joule 6 (1) (2022) 171–184, https://doi.org/10.1016/j.joule.2021.12.017.

[181] G.E. Morse, A. Tournebize, A. Rivaton, T. Chassé, C. Taviot-Gueho, Net al Blouin, The effect of polymer solubilizing side-chains on solar cell stability, Phys. Chem. 118 (17) (2015) 84–97.

[182] A. Guerrero, H. Heidari, T.S. Ripolles, A. Kovalenko, M. Pfannmöller, Set al Bals, Shelf life degradation of bulk heterojunction solar cells: intrinsic evolution of charge transfer complex, Adv. Energy Mater. 5 (2015).

[183] P. Ding, D. Yang, S. Yang, Z. Ge, Stability of organic solar cells: toward commercial applications, Chem. Soc. Rev. 53 (5) (2024) 2350–2387, https://doi.org/10.1039/d3cs00492a.

[184] S. Savagatrup, A.D. Printz, T.F. O'Connor, A.V. Zaretski, D. Rodriquez, E. J. Sawyer, et al., Mechanical degradation and stability of organic solar cells: molecular and microstructural determinants, Energy Env. Sci (8) (2015) 55–80.

[185] S. Rafique, S.M. Abdullah, K. Sulaiman, M. Iwamoto, Fundamentals of bulk heterojunction organic solar cells: an overview of stability/degradation issues and strategies for improvement, Renew. Sustain. Energy Rev. 84 (December 2017) (2018) 43–53, https://doi.org/10.1016/j.rser.2017.12.008.

[186] M. Of, H. Transport, T.O. Enhance, T.H.E. Performance, P.S. Cells, Modification of Hole Transport Layer to Enhance the Performance of Polymer Solar Cells, 2017.

[187] E. Barulina, et al., Improved ultraviolet stability of fullerene-based organic solar cells through light-induced enlargement and crystallization of fullerene domains, Thin Solid Films 757 (2022) 1–26, https://doi.org/10.1016/j.tsf.2022.139394.

[188] A. Uddin, M.B. Upama, H. Yi, L. Duan, Encapsulation of organic and perovskite solar cells: a review, Coatings 9 (2) (2019) 1–17, https://doi.org/10.3390/coatings9020065.

[189] H. Cao, et al., Recent progress in degradation and stabilization of organic solar cells, J. Power Sources 264 (2014) 168–183, https://doi.org/10.1016/j.jpowsour.2014.04.080.

[190] E. çetin Yilmaz, M.K. Yeşilyurt, I.V. öner, G. ömeroğlu, A.N. özakin, Operational stability and degradation of organic solar cells, Period. Eng. Nat. Sci. 5 (2) (2017) 152–160, https://doi.org/10.21533/pen.v5i2.105.

[191] W. Sung, et al., Nanomorphology dependence of the environmental stability of organic solar cells, NPG Asia Mater. 14 (1) (2022), https://doi.org/10.1038/s41427-022-00400-9.

[192] J. Kastner, F. Tomarchio, N. Decorde, M. Kehrer, G. Hesser, A. Fuchsbauer, Integration of inkjet printed graphene as a hole transport layer in organic solar cells, Micromachines 14 (10) (2023) 1–15, https://doi.org/10.3390/mi14101858.

[193] R.E.O. Reese, M. O, A.M. Nardes, B.L. Rupert, D.S.R.D.C. Larsen, M.T. Lloyd, S. E. Shaheen, Ginley, N.D.S. Kopidakis, Photoinduced degradation of polymer and polymer–fullerene active layers: experiment and theory, Adv. Funct. Mater. 20 (20) (2010) 3476–3483.

[194] B. A. Phengdaam , S. Nootchanat , R. Ishikawa , C. Lertvachirapaiboon , K. Shinbo , K. Kato, "Improvement of organic solar cell performance by multiple plasmonic excitations using mixed-silver nanoprisms," J. Sci. Adv. Mater. Dev., p. 264—270, doi: 10.1016/j.jsamd.2021.02.0076.

[195] A.A. Gregory Burwell, Oskar J. Sandberg, Wei Li, Paul Meredith, Matt Carnie, Scaling Considerations for Organic Photovoltaics for Indoor Applications, vol. 6, 2022, https://doi.org/10.1002/solr.202200315, 7.

[196] M.D.M. Faure, B.H. Lessard, Layer-by-layer fabrication of organic photovoltaic devices: material selection and processing conditions, J. Mater. Chem. C 9 (1) (2021) 14–40, https://doi.org/10.1039/d0tc04146g.

[197] J.M. Xinrong Yang, Yiming Shao, Shanshan Wang, Mingxia Chen, Bo Xiao, Rui Sun, Processability Considerations for Next-Generation Organic Photovoltaic Materials, 2023, https://doi.org/10.1002/adma.202307863 [Online]. Available:.

[198] P.C.O. Priscila Gonçalves Vasconcelos Sampaio, Mario Orestes Aguirre González, Paula de Oliveira Ferreira, Priscila da Cunha Jácome Vidal, Jonathan Paulo Pinheiro Pereira, Helder Rodrigues Ferreira, Pedro Carlos Oprime, Priscila Gonçalves Vasconcelos Sampaio, Mari, Overview of printing and coating techniques in the production of organic photovoltaic cells, Int. J. Energy Res. 44 (Issue 13) (2020) 9912–9931, https://doi.org/10.1002/er.5664 [Online]. Available:.

[199] R.P. Peiyao, X.Z. Xue, Pei Cheng, Printing fabrication of large-area non-fullerene organic solar cells, R. Soc. Chem. (9) (2022) 194–219, https://doi.org/10.1039/D1MH01317C.

[200] N.G. Leonard, S.W. Lee, D.W. Chang, J.M. Hodgkiss, D. Vak, Organic photovoltaics' new renaissance: advances toward roll-to-roll manufacturing of non-fullerene acceptor organic photovoltaics, Adv. Mater. Technol. 7 (10) (2022), https://doi.org/10.1002/admt.202101556.

[201] H.L. Yip, A.K.Y. Jen, Recent advances in solution-processed interfacial materials for efficient and stable polymer solar cells, Energy Environ. Sci. 5 (3) (2012) 5994–6011, https://doi.org/10.1039/c2ee02806a.

[202] N.P. Marcela Socol, Hybrid nanocomposite thin films for photovoltaic applications: a review, Nanomaterials 11 (5) (2021), https://doi.org/10.3390/nano11051117 [Online]. Available:.

[203] S.H. Mir, L.A. Nagahara, T. Thundat, P. Mokarian-Tabari, H. Furukawa, A. Khosla, Review—organic-inorganic hybrid functional materials: an integrated platform for applied technologies, J. Electrochem. Soc. 165 (8) (2018) B3137–B3156, https://doi.org/10.1149/2.0191808jes.

[204] M. Socol, N. Preda, Hybrid nanocomposite thin films for photovoltaic applications: a review, Nanomaterials 11 (5) (2021), https://doi.org/10.3390/nano11051117.

[205] S. Srivastava, J.L. Schaefer, Z. Yang, Z. Tu, L.A. Archer, 25th Anniversary article: polymer-particle composites: phase stability and applications in electrochemical energy storage, Adv. Mater. 26 (2) (2014) 201–234, https://doi.org/10.1002/adma.201303070.

[206] M. Philippe, L.N. Clément Sanchez, P. Belleville, Applications of advanced hybrid organic–inorganic nanomaterials: from laboratory to market, Chem. Soc. Rev. (2) (2011).

[207] A. Machín, F. Márquez, Advancements in photovoltaic cell materials: silicon, organic, and perovskite solar cells, Materials 17 (5) (2024), https://doi.org/10.3390/ma17051165.